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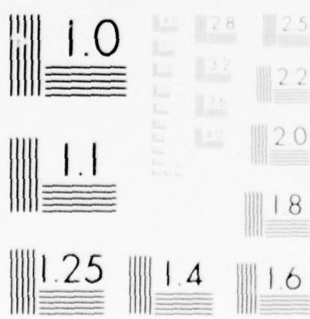

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WEAPON SYSTEM COSTING METHODOLOGY - IMPROVED STRUCTURAL COST ANALYSIS

GENERAL DYNAMICS CONVAIR DIVISION
KEARNY MESA PLANT
5001 KEARNY VILLA ROAD
SAN DIEGO, CALIFORNIA 92138

MAY 1977

TECHNICAL REPORT AFFDL-TR-77-24
FINAL REPORT FOR PERIOD JULY 1975 – FEBRUARY 1977

Approved for public release; distribution unlimited

Prepared for
AIR FORCE FLIGHT DYNAMICS LABORATORY
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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This technical report has been reviewed and is approved for publication.

R. N. Mueller
R. N. MUELLER
Project Engineer

Larry G. Kelly
LARRY G. KELLY, Actg Chief
Advanced Structures Development Br
Structures Division

FOR THE COMMANDER

Howard L. Farmer
HOWARD L. FARMER, Col., USAF
Chief, Structural Mechanics Division
Air Force Flight Dynamics Laboratory

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This report describes a study to improve a previously developed weapon system costing methodology for aircraft airframes and basic structures under Contract F33615-72-C-2083. The methodology is part of a preliminary design level technique for the cost estimation of flight vehicle structures. Applications of the method have indicated a number of areas where further study and development could be expected to provide an advanced state-of-the-art capability. This study was directed towards

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20. Abstract (Continued)

that end. The study was limited to the specific changes consisting of (1) development of complexity factors for technologies and materials represented by the advanced strategic bomber wing carry-through box, (2) modification of raw material cost estimating relationships (CERs) to increase sensitivity to material product form and type of scrappage, (3) investigation of additional assembly techniques and adding or modifying corresponding cost estimating facotrs, (4) modification of existing CERs to include evaluation of variations in the degree of commonality involved, (5) determination of the effect of production rate on recurring production costs, and (6) determination of the variation in learning curve factors due to variation in the type of material or type of construction. Detailed results are described.

FOREWORD

This report was prepared by the Convair Division of General Dynamics, San Diego, California, under USAF Contract F33615-75-C-3148. The contract, titled "Improved Structural Cost Analysis," was initiated under Project 1467.

The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Structures Division, Wright-Patterson Air Force Base, Ohio, under the direction of Mr. R. N. Mueller (AFFDL/FBS) as Project Engineer.

This report covers work conducted from July 1975 to February 1977 and was submitted by the author in February 1977, under Air Force Flight Dynamics Laboratory Report No. TR-77-24 as a Final Report. This report consists of one volume.

The principal author and project leader on this program is Mr. R. E. Kenyon, under the administration of Mr. G. E. Vail, Chief of Economic Analysis. Others who contributed to the studies and who contributed in the preparation of this volume include J. L. Youngs, Economic Analysis and Jess McDaniels, Fort Worth Division.

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SECTION I

INTRODUCTION

This is a study to improve the cost analysis methodology developed under Contract F33615-72-C-2083. This methodology is part of a preliminary design level technique for the cost estimation of flight vehicle structures. It was designed to be sensitive to the structural concepts and materials used and to provide a significant capability for preliminary design level cost analysis and trade studies. Applications of the method to date have, however, indicated a number of areas where further study and development could be expected to provide an advanced state-of-the-art capability. This study is directed towards that end.

The study is limited to the specific changes outlined in the statement of work, consisting of extending the choice of design concepts and materials that can be handled and improving the techniques sensitivity to specific parameters known to have a significant impact upon acquisition costs. The study objectives are defined by the following six tasks:

a. Development of complexity factors for technologies and materials represented by the advanced strategic bomber wing carry-through box.

b. Modification of raw material cost estimating relationships (CERs) to increase sensitivity to material product form and type of scrappage.

c. Investigation of additional assembly techniques and adding or modifying corresponding cost estimating factors.

d. Modification of existing CERs to include evaluation of variations in the degree of commonality involved.

e. Determination of the effect of production rate on recurring production costs.

f. Determination of the variation in learning curve factors due to variation in the type of material or type of construction.

Model logic changes deriving from these studies are to be implemented in the computer program in-house by AFFDL personnel. Data describing the changes are being furnished as part of the study tasks.

The original method provided an approach to design trade-off studies of airframe structure and comprises alternative levels of capability: a trade study cost

estimating method and an airframe system cost estimating method. The first capability involves a technique that allows the designer to compare competing structural designs on a relative cost basis and involves a very detailed level of estimating for basic structure only. The second capability provides estimates at the subassembly level for total airframe costs, including basic structure and fucntional subsystems, to support the evaluation of proposed systems in a system study context. The current study is concerned only with the first of these methods.

The present contract is a follow-on to Air Force Contract F33615-72-C-2083, sponsored by the Structures Division of the Flight Dynamics Laboratory, which was in turn a follow-on to Air Force Contract F33615-70-C-1340, also sponsored by the Structures Division. The earlier study provided for the investigation of representative approaches to cost estimating as they are described in the available literature, the conception and evaluation of new approaches, the final selection of an approach for each of the two required types of estimating, and the development of the selected approaches to the point that their feasibility could be demonstrated. The feasibility study was followed by the second contract, which provided for extending the trade study cost estimating techniques from the horizontal stabilizer to the entire basic structure and for developing the system study method. The results and findings of the first phase were combined with the results of the additional research and study to produce an expanded and updated estimating system. The initial estimating techniques were demonstrated using the horizontal stabilizer for evaluation purposes. Additional test cases were run based on all elements of the aerodynamic surfaces, the fuselage and nacelle components with a final demonstration based on all elements of a single aircraft. These studies, which are described in Reference 1, provide the background for the current improvement study.

The organization of this report is as follows. Section II provides a very brief review of the initial method as background. Then the basis for determining the improvement needed and the improvements themselves are described. Section III discusses approaches and results with respect to each improvement objective. Improvements consist of expansion of the data base, refinements to input data tables, and improvements in the basic estimating relationships. Resulting computer program changes are described in Section IV. The final section discusses conclusions and recommendations.

This report is organized to be supplementary to Reference 1. It's primary purpose is to provide augmentation to the results of that prior study, and thus, it is not a stand alone report.

---

1. R. E. Kenyon, "Weapon System Costing Methodology for Aircraft Airframes and Basic Structures," AFFDL-TR-75-44, Volumes 1 and 2, Contract F33615-72-C-2083, June 1975.

SECTION II

THE RATIONALE FOR METHOD IMPROVEMENT

This section discusses the background and the basis for improvements sought in the trade study cost estimating method. It includes a brief description of the trade study cost estimating method, a review of the findings and testing involved in the original development of the method, and a description of the improvements that are the subject of this study. The description of the method is provided for background information. Results from the original development provide the primary source of direction for improvements. These are briefly reviewed. The last part of this section is devoted to a discussion of improvement objectives and approaches.

2.1 DESCRIPTION OF THE TRADE STUDY METHOD

This section provides an overview of the trade study method. The basic elements of the method are shown in Figure 1.

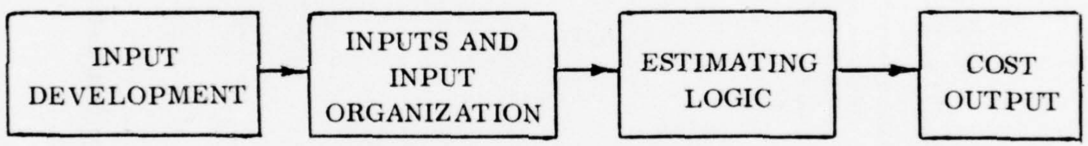

Figure 1. Estimating Process Basic Elements.

Input development relates primarily to the preliminary design interface and in particular the supporting structural synthesis programs. Inputs are categorized by method of handling in the computer program and by the nature of the input. They consist of NAMELIST variables, which vary with design characteristics, and model card inputs consisting of estimating coefficients baselined to the historical data base. The estimating logic consists of a series of cost estimating relationships, which are listed in Appendix A. The cost output is the final element of the estimating process.

Figure 2 gives an outline of the trade study estimating method and the flow of information required. In this description of the method, the discussion will begin with the cost output and work backwards through the various phases of the program to the procedure for development of input data.

Cost Output

The cost output is described and defined by the computer printout formats, samples of which are given in Figures 3 through 6. These represent a complete set of

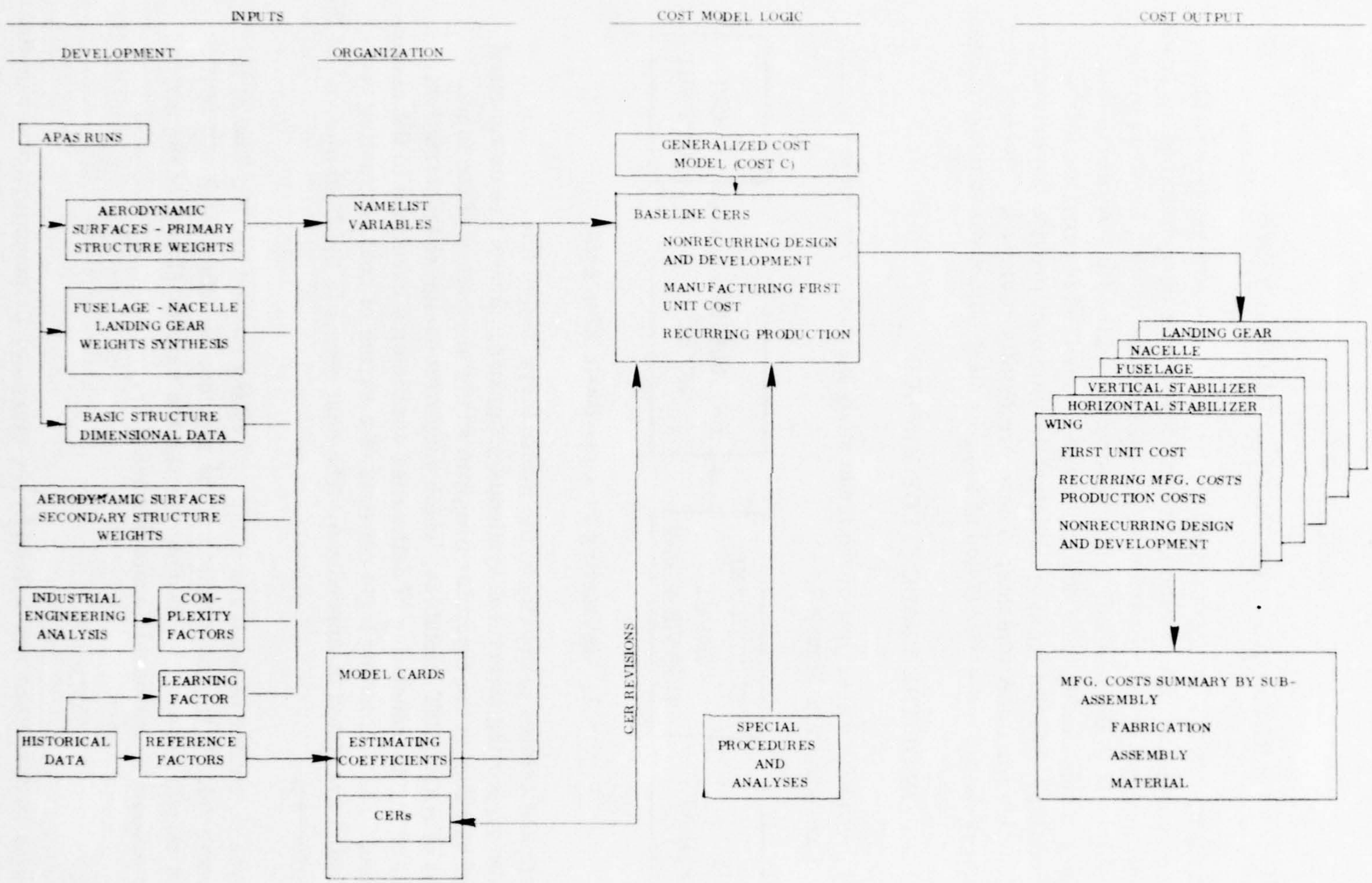

Figure 2. Trade Study Cost Estimating Method.

B-58 TEST CASE
USE OF DECIMAL IMPLIES UNITS IN MILLIONS

FIRST UNIT COST

WING

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	DTAIL FAB HOURS	SUB-ASSY HOURS	MAJOR ASSY HOURS	PRIM-ASSY HOURS	MAJOR MATE HOURS	MATL COST $	TOTAL LABOR HOURS	TOTAL LABOR $	TOTAL $
STRUCTURAL BOX									
RIBS	4539	1061				12629			
SPARS	8898	6387				29503			
COVERS	11758	7696				51651			
ASSEMBLY			40039			68066			
STRUCTURAL BOX SUB-TOTALS	25245	15144	40039			161850			
LABOR COSTS ($)	159739	95256	251845						
SECONDARY STRUCTURE									
LEADING EDGE	4862	4350				5443			
TRAILING EDGE	2421	2160				2168			
AILERONS	42612	24471				14358			
FAIRINGS	9259	7222				9694			
TIPS	6319	5118				4418			
SPOILERS									
FLAPS + FLAPERONS									
ATTACHMENT STRUCTURE	1131	391				3339			
ACCESS + OTHER DOORS	1521	3275				10104			
AIR INDUCTION									
HIGH LIFT DUCTING									
SLATS									
HINGES, BRACKETS, SEALS									
PIVOTS + FOLDS									
CENTER SECTION									
OTHER	14914	8949				15903			
ASSEMBLY			29864			34216			
SECONDARY STRUCTURE SUB-TOT	82099	57337	29864			100242			
LABOR COSTS ($)	516403	360648	187842						
WING SUBTOTAL	107344	72481	69903			262091			
WING REWORK	10734	7248	6990			26209			
WING TOTAL	118078	79729	76893	21976	10988	288101			
LABOR COSTS ($)	742711	501494	483655	139229	69114				
TOTALS							307663	1935203	2223503

Figure 3. Wing First Unit Cost.

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RDT+E COSTS 30

WING

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	DTAIL FAB HOURS	SUB-ASSY HOURS	MAJOR ASSY HOURS	PRIM-ASSY HOURS	MAJOR MATE HOURS	MATL COST $	TOTAL LABOR HOURS	TOTAL LABOR $	TOTAL $
STRUCTURAL BOX									
RIBS	42701	9374				315769			
SPARS	82734	59429				737673			
COVERS	109408	71612				1291437			
ASSEMBLY			372564			1701872			
STRUCTURAL BOX SUB-TOTALS	234902	140315	372564			4046751			
LABOR COSTS ($)	1477536	886356	2343428						
SECONDARY STRUCTURE									
LEADING EDGE	45244	45127				136093			
TRAILING EDGE	22526	20399				54199			
AILERONS	396504	231424				371488			
FAIRINGS	76851	67205				247377			
TIPS	58739	47627				110454			
SPOILERS									
FLAPS + FLAPERONS									
ATTACHMENT STRUCTURE	11081	22290				83470			
ACCESS + OTHER DOORS	14150	30476				252540			
AIR INDUCTION									
HIGH LIFT DUCTING									
SLATS									
HINGES, BRACKETS, SEALS									
PIVOTS + FOLDS									
CENTER SECTION									
OTHER	138779	83267				395127			
ASSEMBLY			277881			855518			
SECONDARY STRUCTURE SUB-TOT	763934	547515	277881			2506365			
LABOR COSTS ($)	4805144	3443867	1747873						
WING SUBTOTAL	998836	688430	650445			6553116			
WING REWORK	99894	68843	65045			655312			
WING TOTAL	1098720	757273	715490	205719	102859	7208428			
LABOR COSTS ($)	6910948	4763245	4500431	1293970	646985				
TOTALS							2.8801	18.1156	25.3240

Figure 4. Wing RDT&E Costs.

AEROSPACE VEHICLE STRUCTURAL COSTS

RECURRING AIRFRAME PRODUCTION COSTS (SUMMARY)

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	WING HOURS	HORT HOURS	VERT HOURS	FUSE HOURS	NACE HOURS	LDG GEAR HOURS	SUB-TOTAL HOURS	DOL LAR COSTS	PROD UNITS
RDT+E									
SUSTAINING ENGRG							1.366	8.961	30
SUSTAINING TOOLING							18.593	116.391	
MANUFACTURING									
DETAIL FAB	1.9939		.1333	.7195	.5536	.0023	2.563	15.741	
ASSEMBLY	1.4510		.2033	1.3250	.6810	.0197	3.680	23.147	
PRIMARY ASSY + MAJOR MATE							.742	4.667	
QUAL CONTROL							.692	4.736	
MATERIAL + OTHER	7.2067		.8293	7.2450	2.3650	7.2385		24.685	
MAJOR MATE MATERIAL								3.484	
TOTALS							27.576	232.012	
PROCUREMENT ARTICLES									
SUSTAINING ENGRG							.860	5.639	86
SUSTAINING TOOLING							10.230	64.041	
MANUFACTURING									
DETAIL FAB	1.1920		.1452	.7840	.6032	.0025	2.727	17.153	
ASSEMBLY	1.5811		.2216	1.4438	.7421	.0215	4.010	25.223	
PRIMARY ASSY + MAJOR MATE							.808	5.085	
QUAL CONTROL							.755	5.161	
MATERIAL + OTHER	18.3568		2.1125	18.4543	6.0241	18.4378		63.385	
MAJOR MATE MATERIAL								8.874	
TOTALS							19.390	194.561	

Figure 5. Recurring Airframe Production Costs (Summary).

Aerospace Vehicle Structural Costs

Nonrecurring Design and Development Costs

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	Wing Hours	Hort Hours	Vert Hours	Fuse Hours	Nace Hours	Log Gear Hours	Sub-Total Hours	Dollar Costs
Basic Struc Design Engr	.152		.029	.201	.191	.079	.652	4.277
Configuration Design Engr							.750	4.919
Engineering Material								.492
Total Trade Study Engr							1.402	9.688
Basic Tool Mfg Hours	2.1		.17	2.08	.98		5.33	
Rate Tooling Mfg Hours							1.31	
Total Tool Mfg							6.64	41.57
Basic Tool Engrg Hours							2.132	
Rate Tool Engrg Hours							.1965	
Total Tool Engrg							2.33	13.84
Mfg Devel + Plant Engr							.13	.80
Total Matl + Other Dollars								6.64
Manufacturing Support Dollars								.492
Quality Control							.41	2.78
Totals							10.912	66.122

Figure 6. Nonrecurring Design and Development Costs.

computer printouts for one structural element, except for additional printouts for alternative production quantities (to a maximum of two). The remaining structural elements comprising the airframe are handled in a comparable manner. A complete set of output data represents thirty-six different computer printouts as summarized in Table 1.

Wing First Unit Cost, shown in Figure 3, involves definition of cost by primary and secondary structural element and by element of cost, i.e., manufacturing labor, broken down into fabrication and assembly tasks, and production material. The cost of production units is estimated in the detail shown in Figure 4 (for RDT&E production units). This breakout is identical to the one for first unit cost. These estimates are made simply by a learning curve projection of the first unit values.

Figure 5 provides a summary of recurring airframe production costs. This summary is provided for each of the production quantities estimated. It summarizes manufacturing items of cost and provides for the estimating of sustaining engineering and tooling for the various production quantities. Manufacturing costs are obtained from the detailed printouts. The item "assembly," comprises hardware element subassembly and major assembly as defined for primary and secondary structure. Nonrecurring design and development costs are given as shown in Figure 6 and consist of engineering labor and material; tool engineering, manufacturing, and material; manufacturing support; quality control, and manufacturing development. These are for structural subsystems only.

Cost Model

The Cost Model, comprising the cost estimating logic, consists of sets of CERs developed for each of the items of cost identified in the computer printouts. These CERs and their derivation are described in Reference 1. Figure 7 gives examples of manufacturing first unit CERs for labor and material. Many other forms are involved. Manufacturing First Unit Cost is an estimating convention based on using theoretical first unit cost as the basis for estimating manufacturing costs.

It is sometimes necessary to augment the standard procedure, as represented by the CERs, with special procedures and analyses. These require definition for each individual case and are generally not of a nature to permit incorporation in the main body of CERs.

The estimating method makes use of an existing general cost program, designated COSTC, that operates as a data manager program and handles the cost estimating logic as a program input. This provides a simple means of modifying cost

Table 1. Summary of Cost Printouts for a Trade Study Estimate.

Hardware Component	Type of Cost Printout					
	First Unit Cost	RDT&E Units Cost	Production Units Quantity 1	Production Units Quantity 2	Nonrecurring Design & Development	Recurring Production Summary
Aerodynamic Surfaces:						
Wing	X	X	X	X	X	X
Horizontal Stabilizer	X	X	X	X	X	X
Vertical Stabilizer	X	X	X	X	X	X
Fuselage	X	X	X	X	X	X
Nacelles	X	X	X	X	X	X
Landing Gears	X	X	X	X	X	X

Rib Detail Fabrication Hours

$$H_1 = \frac{(W_i\ CF_i + W_i\ CF_i + W_i\ CF_i)\ (HF_i)\ (WT_i)^{E_i}}{WT_i}$$

where:
- W_i = Weight of ribs of three alternative construction and material types represented by corresponding complexities.
- CF_i = Complexity factor corresponding to rib type
- WT_i = Sum of the rib weights
- HF_i = Fabrication hours per pound for structural component for baseline configuration.
- E_i = Weight-scaling exponent.

Rib Subassembly Hours

$$H_i = \frac{(W_i\ CM_i + W_i\ CM_i + W_i\ CM_i)\ (HF_i)\ (WT_i)^{E_i}}{WT_i}$$

where:
- CM_i = Complexity factor for given material and construction technique.
- HF_i = Subassembly hours per pound for baseline configuration.
- E_i = Weight-scaling exponent.

Rib Structural Material Cost

$$M_i = W_i^G\ (RMC_i)\ (SF_i)$$

where:
- RMC_i = Raw material cost per pound.
- SF_i = Scrappage factor
- G = Weight scaling exponent

Figure 7. CER Examples - Trade Study Estimating Method for Manufacturing First Unit Cost.

estimating relationships. These are accomplished simply by changing an input model card and the corresponding input variables(s).

The total set of CERs generates the variable input requirement entered in the program as NAMELIST variables. These, together with the model cards, constitute an input package. The model cards, which include the CER entries, constitute an input whenever they are to be revised. They may be revised for either of two reasons: (1) to change the form of a CER, or (2) to change an estimating coefficient. These coefficients appear as constants within the CERs, and comprise such items as baseline costing factors, scaling factors, and other factors based on historical data.

The computer program deck set-up is illustrated by Figure 8. The program deck consists of the COSTC general cost program. Inputs comprise NAMELIST SIZE, NAMELIST CURVE, NAMELIST SUMMARY, and Model Card entries. Sample model card entries are illustrated in Figure 9. This is a very limited sample, the total Model Card Deck consisting, as it does, of approximately 650 entries. Figure 10 gives an example of the relationship between inputs (and input sources) and the CER. A general idea of the input organization is furnished by Figure 11. It should be noted that numerous additional CER forms and input relationships are involved. Input development is illustrated by Figure 12.

As shown by Figure 12, various design synthesis program runs are required to support the development of inputs. These provide design information required in the estimating process. There are three such programs: (1) An Automated Program for Aerospace - Vehicle Synthesis (APAS), (2) A Program for Development of Aircraft Fuselage, Nacelle and Landing Gear Weights, and (3) The Tip, Leading and Trailing Edge Analysis Program. The first of these in turn supports the second. The third program operates independently. A technical description of these programs is given in Reference 1. Each of these programs also, obviously, has an input requirement.

The weight analysis for aerodynamic surfaces primary structure involves the use of correlation factors applied to the output of APAS. These factors are in turn based on weights research data from other studies. A separate design synthesis and weight analysis procedure, the Tip, Leading and Trailing Edge Analysis Program, is used for aerodynamic surfaces secondary structure. These results, combined with those for primary structure, result in data such as shown in Table 2. Correlation factors are calculated as the ratio of actual weight to synthesis weight. They provide a measure of the credibility of the synthesized weight and can be used as analogs in estimating similar structural elements.

The weight analysis for fuselage structure, both primary and secondary, is handled by the Program for Development of Aircraft Fuselage, Nacelle and

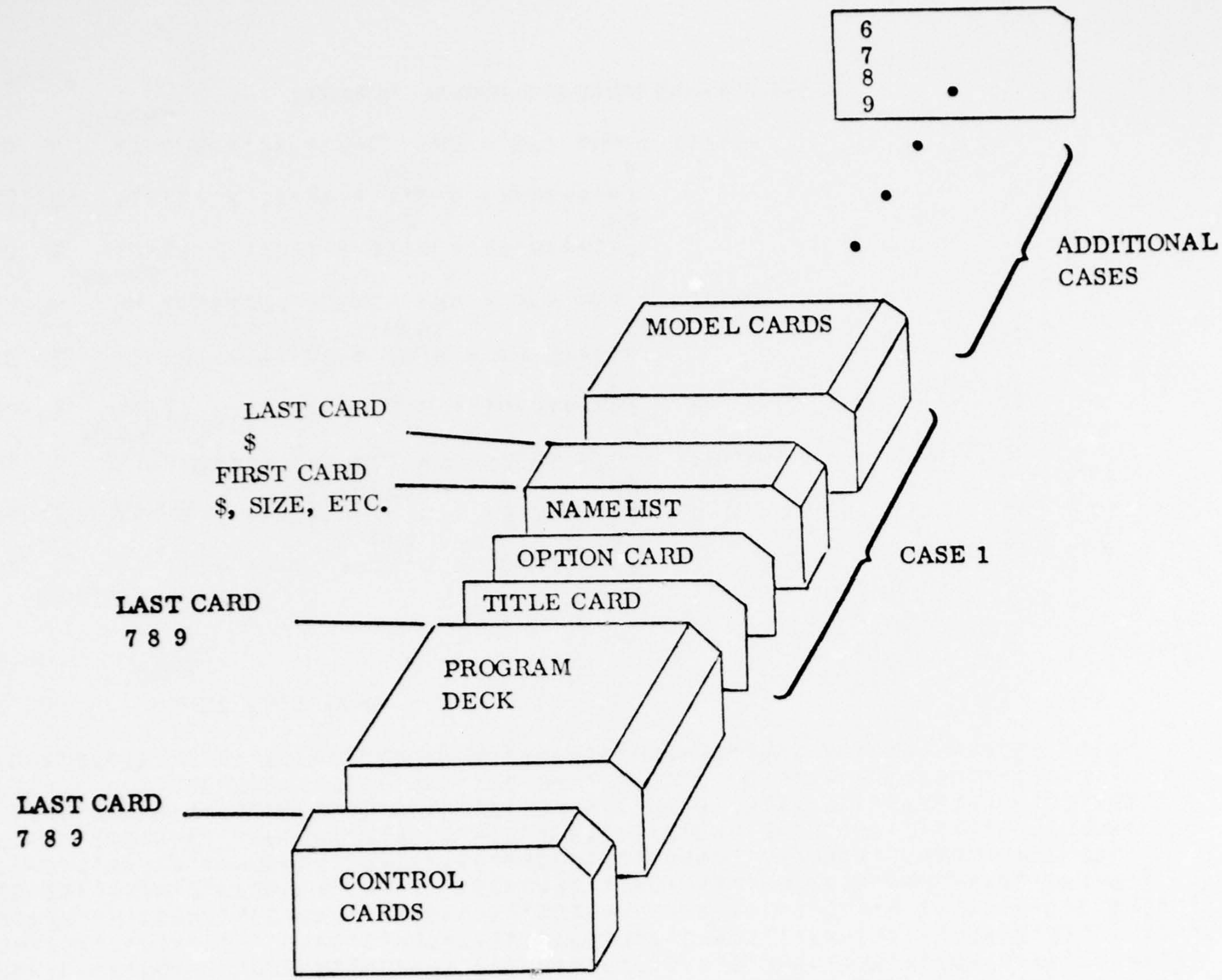

Figure 8. Computer Program Deck Set-Up.

```
    CARDS   350WNG   HTL   VTL   FLG   NAC   LOG
$SIZE
 W1=70.,CF1=.51,W2=270.,CF2=.99,W3=540.,CF3=1.,W4=1000.,CF4=.640,W5=693.,
 CF5=1.72,W6=250.,CF6=1.,W7=5114.,CF7=3.5,CM1=2.03,CM3=1.,CM4=3.34,CM6=1.,
 CM7=3.5,CN=60.,RN=8.,SNE=31.,SFE=30.,RP=50.,TS4=.1,FF1=1.2,FF2=2.,CB1=1.75,
 WD1=348.7,CC1=2.,CB2=4.,WD2=93.2,CC2=4.5,CB3=4.5,WD3=1135.2,CC3=4.75,CB4=2.7,
 WD4=757.7,CC4=2.5,CB5=2.5,WD5=265.9,CC5=2.7,CB8=3.,WD8=101.2,CC8=2.31,CB9=3.,
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 SF13=1.2,RMC14=50.,SF14=1.2,RMC17=18.,SF17=5.3,RMC18=50.,SF18=3.,RMC25=40.,
 SF25=2.,FM1=2.5,FM2=1.7,EH=540.,WAMPR=12156.,ECLF=6.56,TMF=7500.,TAM=3.,
 THC=6.26,TEC=5.94,TDC=6.,RQC=6.84,PN1=1.,PN2=30.,PN3=36.,RM=6.29,RT=6.26,
$
C            FIRST UNIT COST
C           WING
N 9
T
C    STRUCTURAL BOX
F 31  1    (5,1) / (5,3) * 51.0 * (5,3)**.67
                         HF1            E1
F 31  2    (9,2) / (5,3) * 14.5 * (5,3)**.67
                         HF4            E4
F 31  6    W1 WNG**.77 * RMC1 WNG * SF1 WNG + (12,3)
D        RIBS
F 32  1    (6,1) / (6,3) * 52.0 * (6,3)**.67
                         HF2            E2
F 32  2    (10,2) / (6,3) * 19.0 * (6,3)**.67
                          HF5            E5
F 32  6    W4 WNG**.77 * RMC4 WNG * SF4 WNG + (12,6)
D        SPARS
F 33  1    (7,1) / (7,3) * 11.0 * (7,3)**.67
                         HF3            E3
F 33  2    (11,2) / (7,3) * 7.2 * (7,3)**.67
                          HF6           E6
F 33  6    W7 WNG**.77 * RMC7 WNG * SF7 WNG + (12,9)
D        COVERS
```

Figure 9. Examples of Model Card Entries.

SIZE PARAMETER

APAS PROGRAM

SECONDARY STRUCTURE WT. EST.

OTHER WT. ESTIMATION

COMPLEXITY FACTOR

COMPLEXITY FACTOR TABLES

BASE LINE EXPONENT

HISTORICAL DATA

$$H_i = \left[\frac{\left(W_i\, CF_i + W_i\, CF_i + W_i\, CF_i\right)\left(HF_i\right)\left(WT_i\right)}{WT_i}\right]^{E_i} \times (R)$$

BASELINE ESTIMATING COEFFICIENT

HISTORICAL DATA

LABOR RATE

OTHER INPUTS

Figure 10. Input and Input Source Examples.

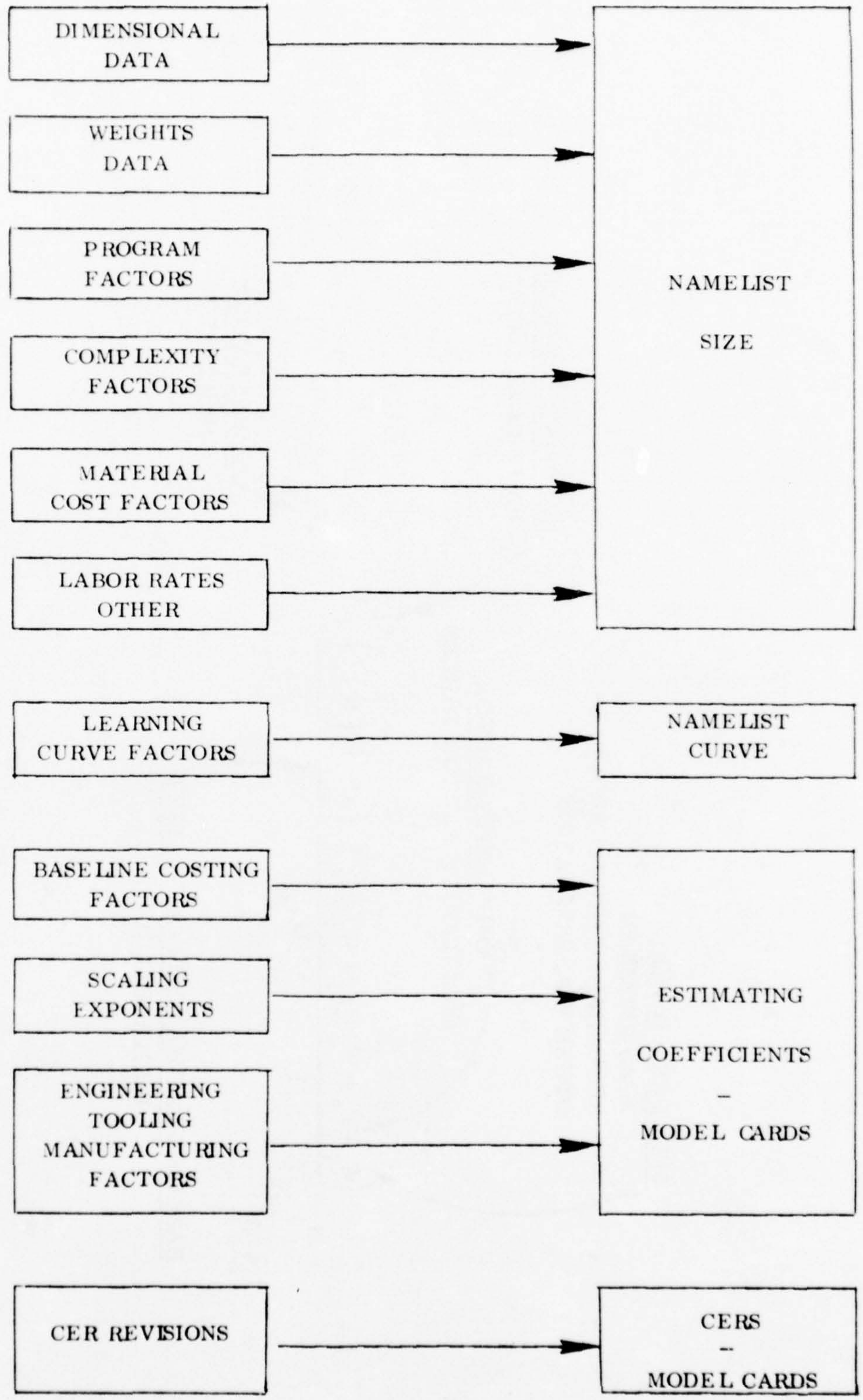

Figure 11. Cost Model Input Summary.

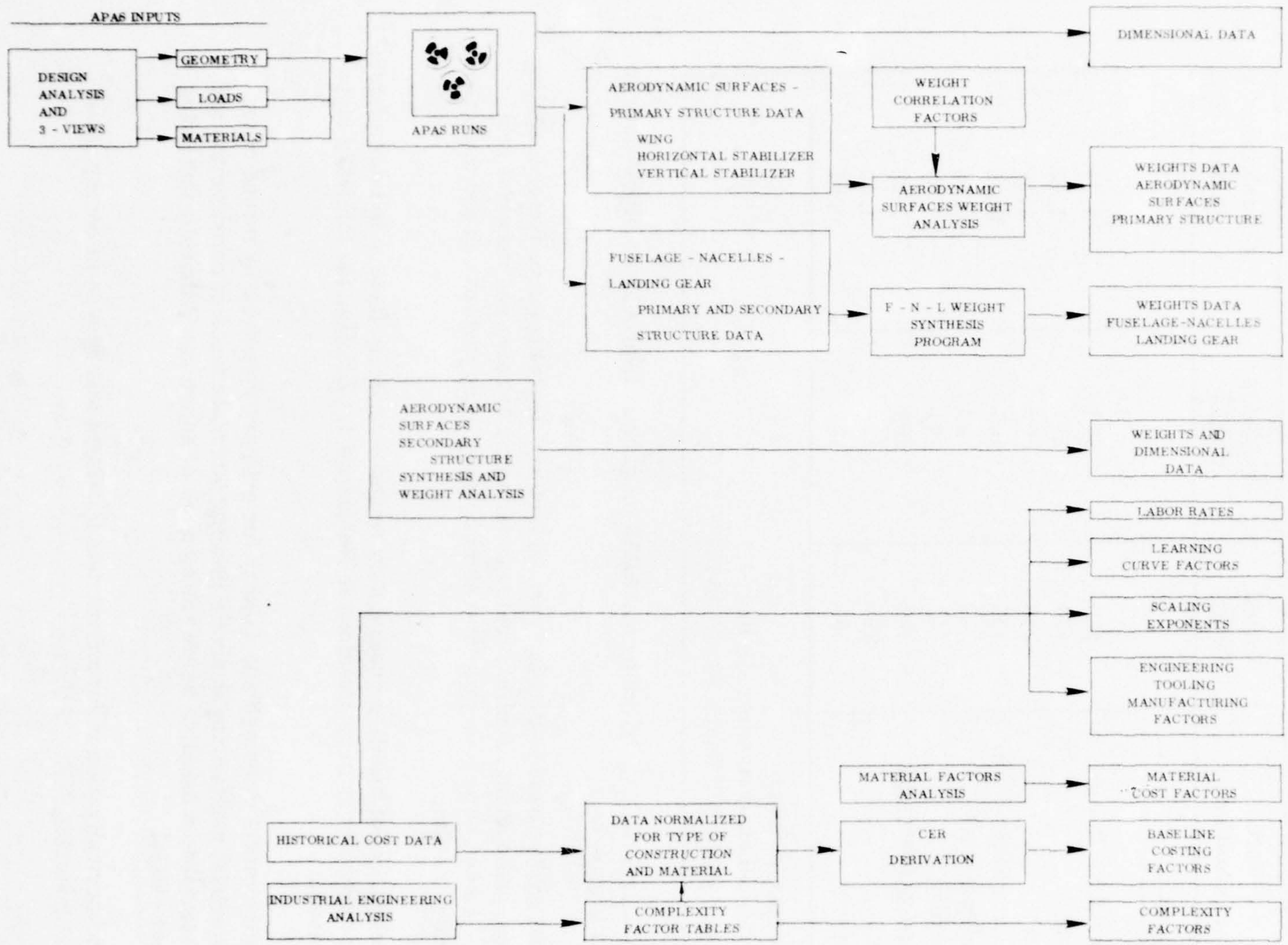

Figure 12. Input Development.

Table 2. Aerodynamic Surfaces Structural Weights

Part Definition	Actual Weight	Synthesis Weight	Correlation Factor
A-X Wing			
Inter-Spar Cover	750	672	1.12
Spars	410	286	1.43
Ribs	316	60	5.27
Leading Edge & Tip	125	166	0.75
Trailing Edge	52	92	0.56
Ailerons	49	24	1.87
Flaps & Foreflaps	359	281	1.28
Slats	278	198	1.40
Spoilers	83	134	0.67

Does not Include:

1. Misc. Structure: 88 lbs
2. Aileron Balance Wts.: 45 lbs

Landing Gear Weights, driven by the APAS program. It provides weights data as shown in Figure 13.

Historical data is used to develop various factors: learning curve factors; scaling exponents; engineering, tooling, and manufacturing factors; and material cost factors. Tables have been prepared summarizing these factors and are described in the study results.

The development of baseline costing factors and complexity factors is interrelated. Their development is fully explained in Reference 1. Briefly, the following steps are involved:

a. Development of complexity factors for primary structure by means of an industrial engineering analysis relating alternate types of construction and material to a baseline hardware element of known cost, thereby indicating cost ratios.

b. The normalization of historical data by weight and by type of construction and material.

B-58A TEST CASE

		PANELS	LONGERONS	FRAMES	WEBS	NON STRUC	HORZ-TOTALS
BASIC SHELL	1783.0	2877.0	178.0	537.2	488.0	0.0	4080.0
COCKPIT PROVISIONS	222.0	55.5	55.5	22.2	66.6	22.2	222.0
NLG DOOR	104.0	93.6	10.4	0.0	0.0	0.0	104.0
NLG CUTOUT / LOAD INTRODUCTION	76.0	0.0	67.8	15.0	0.0	0.0	76.0
WING REACTION BODY TIE	282.0	141.0	28.2	112.8	0.0	0.0	282.0
TAIL PROVISIONS	157.0	78.5	78.5	0.0	0.0	0.0	157.0
WINDSHIELD AND CANOPY	957.0	0.0	0.0	0.0	0.0	957.0	957.0
FWD VERTICAL INERTIA	94.0	0.0	0.0	0.0	0.0	0.0	0.0
AFT VERTICAL INERTIA	42.0	0.0	0.0	0.0	0.0	0.0	0.0
FWD SIDE BENDING	188.0	0.0	0.0	0.0	0.0	0.0	0.0
AFT SIDE BENDING	354.0	0.0	0.0	0.0	0.0	0.0	0.0
FWD FUEL INERTIA	7.0	0.0	0.0	0.0	0.0	0.0	0.0
AFT FUEL INERTIA	77.0	0.0	0.0	0.0	0.0	0.0	0.0
AFT ENGINE BENDING	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AFT HORIZ TAIL BENDING	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FUEL PROVISIONS	546.0	0.0	0.0	0.0	0.0	0.0	0.0
ARRESTING GEAR PROVISIONS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CATAPULT/HOLDBACK FUS TOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CATAPULT/HOLDBACK NLG TOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ENGINE PROVISIONS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DUCT PROVISIONS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MLG DOORS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MLG CUTOUT/LOAD INTROD	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EXTERNAL STORES PROV	208.0	41.6	62.4	104.0	0.0	0.0	208.0
SPEED BRAKES	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BOMB/MISSLE BAY CUTOUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B/M BAY DOORS+MECH CONVENT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B/M BAY DOORS+MECH ROTARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CABIN FLOORING+SUPPORT TRN	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CABIN WINDOWS TRANSPORTS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PRESSURE WEB+SEALANT TRN	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AIR EXTRACTION PROV TRN	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CARGO LOADING RAMP+ACC TRN	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MLG EXTERNAL FAIRINGS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SIDE LOADING DOOR+MECH	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CLAMSHELL DOORS+MECH	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLAT CARGO CLEARANCE DOORS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FUEL TANK FLOORING	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SWING TAIL/NOSE PROVISIONS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OVER WING FAIRING	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WING SLOT SEAL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WING GLOVE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WINDSHIELD FAIRING	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BODY CONFIG PENALTIES	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FUSELAGE MISC WEIGHT	219.0	43.8	43.8	43.8	43.8	43.8	219.0
TOTAL BODY	6716.0	3331.0	517.6	835.0	598.4	1023.0	6305.0

BODY ACTUAL WEIGHT	6174.0
BODY PREDICTED WEIGHT	6305.0
EMPIRICAL WEIGHT FACTOR	0.973
SEMI-ANALYTICAL FACTOR	0.921

Figure 13. Fuselage-Nacelle-Landing Gear Structural Weights.

BEST AVAILABLE COPY

c. The derivation of CERs from the normalized data, assuming that the significant cost related variables are weight, type of construction, and type of material, and further that a consistent scaling relationship is applicable.

d. The continuing collection of historical data and update of the CER derivations.

The industrial engineering analysis investigates manufacturing operations associated with various categories of hardware construction and material types and determines a numerical relationship to a nominal element of hardware that utilizes a baseline type of construction and material. The individual manufacturing operations are evaluated by means of standard hours, and a ratio of cost is established as a measure of complexity.

The original intent of this study (Contract AF33615-70-C-1340) was to deal only with primary structure. It was recognized early on, however, that the secondary structure was of equal significance from a cost standpoint, and the effort was redirected accordingly. Hardware elements making up secondary structure do not tend to fall into type of construction categories as conveniently as do those of primary structure. This complication is reflected in the complexity factor tables for secondary structure, as discussed in Reference 1.

A provision is included in the method for applying learning curve factors at the detailed level shown in Figure 3. Development of the factors themselves was not included in the original study.

Labor rates are inputs to the model. Economic escalation relating to labor may be handled through these inputs. Variations in labor costs, as for example differences between manufacturers, can also be accounted for.

2.2 FINDINGS OF THE METHOD DEVELOPMENT STUDY

Evaluation of the methodology occurred throughout the previous study during development. As much as possible, CERs were developed and evaluated against a selected data base, test cases were run at the major component level, and a final method demonstration was conducted. Test cases and estimating results are described in References 1 and 2. An assessment of the potential for the method for further development was made. Several additional studies suggested themselves from the conclusions and recommendations developed. On the basis of these, the current study was formulated, resulting in the objectives described in the next section.

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2. R. E. Kenyon, "Techniques for Estimating Weapon System Costs," AFFDL-TR-71-74, Final Report, Contract F33615-70-C-1340, April 1972.

2.3 IMPROVEMENTS SOUGHT

As it currently exists, the trade study estimating method handles a fairly large but fixed quantity of design concepts and material choices in the detail required for design-to-cost trade studies that occur in the preliminary design of structural concepts. The technique provides a significant capability for preliminary cost analysis and trade studies, however, certain areas exist where advancement in the state-of-the-art is particularly desireable. The following discussion enumerates these and describes the technical approach required for their accomplishment.

2.3.1 ADVANCED METALLIC STRUCTURES COMPLEXITY FACTOR DEVELOPMENT. The three fold objective of this task was to develop specific complexity factors, within the context of the trade study method outlined in Reference 1, for a wing carry-through box for an advanced strategic bomber and to use these factors as analogs for the development of complexity factors for spars, ribs, wing covers, longerons, and frames for the materials and manufacturing technologies developed by the Advanced Metallic Structures Program for the wing carry-through box. In addition, the impact on learning curve slopes, tooling factors, and other nonrecurring cost factors were to be assessed for the advanced technology involved.

Cost and weight data were collected from the reports on the Advanced Metallic Structures Program, References 3 and 4, and from the Fort Worth Division personnel involved in that program. The level of detail at which complexity factors were to be developed is shown in Figure 14. This hardware breakdown is taken from Reference 3. The principal source of cost and weights data was Reference 4. More detailed supporting data were developed during the course of the above program and are referred to as necessary to provide backup for the development of complexity factors.

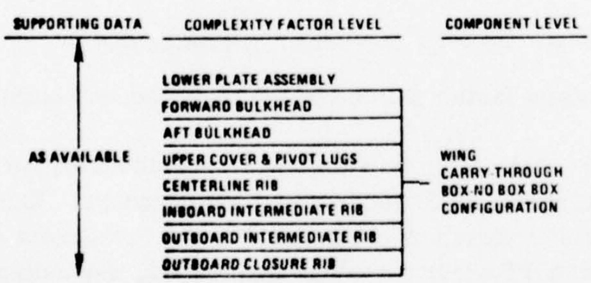

Figure 14. Complexity Factor Level of Detail.

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3. C. E. Hart, Et. Al., "Advanced Metallic Air Vehicle Structure Program: Phase II - Detail Design and Analysis," Technical Report AFFDL-TR-74-17, January, 1974.

4. Bissell, R. D., et al, "Advanced Metallic Air Vehicle Structure Program: Technical Report - Summary," Volume II - Fabrication," Contract F33615-73-C-3001.

Manufacturing methods used in the fabrication of parts listed in Figure 14 had to be analyzed to determine the basis for extending these complexity factors to other elements of primary structure; i.e., ribs, spars, wing covers, longerons, and frames. High-cost steps in the manufacturing process were to be identified so that their occurrence in future designs could be recognized. Structural concepts had to be categorized, materials identified, comparisons made to a baseline construction method, and cost ratios developed in the form of complexity factors. These values could then be made available for normalization against the current data base.

Cost data were also available for design and tooling of the advanced structure wing carry-through box, manufacturing estimates had been made for assumed production quantities. These data provide the basis for analyses to determine increments of cost attributable to the advanced technology represented and, in the case of learning curves, to determine change in slopes as well as initial costs.

2.3.2 RAW MATERIAL COSTS. The current estimating method uses an estimating relationship of the following form for estimating the cost of structural material for primary and secondary structure:

$$M = WD^{G} \ (RMC)\ (SF)$$

where

M = material cost for structural components

WD = weights of the components being estimated

G = weight-cost scaling exponent

RMC = raw material cost per pound by component

SF = scrappage factor related to the material and component estimated.

For primary structure, this form is expanded to provide additive expressions for up to three different types of material in a given component. Each term, except G, is expressed as a series indexed to correspond to the component estimated. The terms RMC and SF have different meanings and values, depending upon whether primary or secondary structure is being considered. Tables have been developed for primary and secondary structure for each term, except in the case of the secondary structure scrappage factor.

During this study, these look-up tables were expanded. In the case of raw material costs, a cost per pound matrix relating raw material cost to different material product forms was developed. This is necessary to differentiate

low-cost forms such as sheet and billet from more expensive forms such as forgings and formed extrusions.

In the case of scrappage factors, expansion is needed to allow for the direct input of multiple scrap factors associated with scrap due to material removal and scrap due to damaged or inferior quality parts. Scrap factors should be related to type of construction and type of material.

2.3.3 <u>CONSIDERATION OF ADDITIONAL ASSEMBLY TECHNIQUES.</u> In the current estimating method, assembly costs are estimated by a series of cost estimating relationships for:

a. Subassembly of primary structure element: ribs, frames, spars, longerons, and covers

b. Basic structure assembly

c. Subassembly of secondary structure elements with elements determined by the component being estimated.

d. Secondary structure assembly

e. Primary assembly

f. Major mate

The CERs used in each category are described in Appendix A. This body of CERs is sensitive to the cost of assembly through a series of size parameters and estimating factors. The size parameters consist of weights and dimensional data. The estimating factors relate size parameters to the cost of various assembly operations.

For the current estimating method, factors are based upon historical data that relates to a limited set of assembly techniques. The study was thus to be concerned with determining the impact on cost when advanced techniques are used. Techniques considered were: (1) automatic riveting, (2) interference-fit fasteners, (3) diffusion bonding, and (4) adhesive bonding. Comparisons of assembly costs using alternative assembly techniques based upon selected manufacturing samples were needed, and modified factors needed to be determined. In addition, a comparison was to be made of the relative cost of assemblying structures with and without fuel storage. Historical data was also analyzed in this latter case in an attempt to identify cost variation attributable to this design difference.

2.3.4 EVALUATION OF COMMONALITY. The introduction of commonality into a design may be expected to reduce manufacturing costs. The existing set of CERs, as described in Appendix A, was to be analyzed to determine ways in which they could be modified to give effect to the degree of commonality involved in a particular design. In the case of primary structure, since individual parts are identified, it was thought that this could be accomplished by a count of similar parts. In the case of secondary structure, a general factor related to some scale of commonality is needed for application within the existing set of secondary structure CERs.

2.3.5 PRODUCTION RATE EFFECTS. Studies have shown that production rates have an effect on production costs. An improvement in method is needed to give effect to production rate variation. This improvement was to be based on a review of the results of other studies as well as in-house studies to determine what could be incorporated into existing recurring production cost estimating relationships.

2.3.6 LEARNING CURVES. In the current estimating method, recurring production costs are projected by means of learning curves at the level of detail used to estimate first-unit costs. This provides for the evaluation of differences in learning introduced by the substitution of alternative materials and construction methods at a relatively low level of detail. The algorithm used for calculating recurring cost, given the first-unit cost, is:

$$\text{Cost estimated} = P1 \sum_{P2}^{P3} i^{x}$$

where,

P1 = first-unit cost,

P2 = beginning point of the projection,

P3 = end point of the projection,

i = series of production units covered,

$$x = \frac{\ln P4}{\ln 2}, \text{ where}$$

P4 = relevant learning curve factor expressed as a decimal fraction.

For a given hardware component, this calculation is repeated for each hardware element. An input value is provided for each calculation. Variation in this value

occurs due to the type of cost involved (i.e., detail fabrication, subassembly, major assembly, or material cost), and due to the type of material and construction of an individual element of hardware. Table 3 summarizes the set of inputs needed for runout of detail fabrication of primary and secondary structure for a complete aircraft basic structure. Similar sets of inputs are required for assembly and production material cost runout.

Table 3. Learning Factors for Detail Fabrication for Primary and Secondary Structure.

Symbol	Wing	Horizontal	Vertical	Fuselage	Nacelle	Landing Gear
PC11	Ribs	Ribs	Ribs	Frames	Not used	Not used
PC12	Spars	Spars	Spars	Longerons	Not used	Not used
PC13	Covers	Covers	Covers	Covers	Not used	Not used
PC14	Not used	Not used	Not used	Not used	Not used	Not used
PC15	Leading Edge	Leading Edge	Leading Edge	Cockpit	Cowling	Brakes
PC16	Trailing Edge	Trailing Edge	Trailing Edge	Nose LG Door	Pylon	Brake Controls
PC17	Ailerons	Fairings	Fairings	Wing Box	Main LG Door	Wheels
PC18	Fairings	Tips	Tips	Tail Attachment	Not used	Tires
PC19	Tips	Attach Structure	Attach Structure	Windshield	Not used	Oleos
PC110	Spoilers	Access	Access	Main LG Door	Not used	Axles
PC111	Flaps	Hinges	Hinges	Fuel Provisions	Not used	Drag Braces
PC112	Attach Structure	Pivots	Rudder	Engine Provisions	Not used	Not used
PC113	Access Doors	Center Section	Not used	Duct Provisions	Not used	Not used
PC114	Air Induction	Elevators	Not used	Stores Provisions	Not used	Not used
PC115	High-Lift Ducting	Balance Weights	Not used	Speed Brakes	Not used	Not used
PC116	Slats	Not used	Not used	Cabin Flooring	Not used	Not used
PC117	Hinges	Not used	Not used	Windows	Not used	Not used
PC118	Pivots & Folds	Not used	Not used	Doors	Not used	Not used
PC119	Center Section	Not used	Not used	Not used	Not used	Not used
PC120	Other	Not used	Not used	Not used	Not used	Not used
PC121	Not used	Not used	Not used	Not used	Not used	Not used

Data is needed to show the variation in learning due to type of material and type of construction. This would then provide the basis for a table of suggested alternative values to be used as a source of estimating input values required by the existing estimating method.

2.3.7 COST MODEL COMPUTER PROGRAM CHANGES. The implementation of the model logic changes derived from the above studies were to be accomplished in-house by AFFDL personnel. Suitable data describing such changes is a part of the above tasks.

SECTION III

DISCUSSION OF IMPROVEMENTS

3.1 COMPLEXITY FACTOR DEVELOPMENT FOR ADVANCED METALLIC STRUCTURES. The threefold objective of this task was: (1) to develop specific complexity factors, within the context of the existing trade study method, for advanced structures using data obtained from a wing carry-through box of an advanced strategic bomber; (2) to extend these factors by analog for the development of complexity factors for spars, ribs, wing covers, longerons, and frames as part of the existing method, representing materials and manufacturing technologies exemplified by the wing carry-through box; and (3) to determine the impact of the represented advanced technology on tooling factors, nonrecurring cost factors, component assembly and learning curve slopes.

The following steps were involved:

a. The acquisition of data from the Fort Worth Division, AFFDL sponsored, Advanced Metallic Air Vehicle Structure development program. This data consisted of design, tooling, fabrication, assembly and material cost data; weights data, data on material and type of construction; and material form and usage data.

b. The analysis of this data using accepted industrial engineering and cost analysis techniques to determine cost-weight relationships.

c. The development of factors for fabrication and assembly hours estimating at the wing carry-through box level and review of the corresponding reference cost per pound values for fabrication and assembly.

d. The collection of weight and cost data at the assembly and part level and the analysis of data at these levels to investigate cost-weight relationships and to determine complexity relationships and reference cost factors.

e. The extension of these complexity factors by analogy to primary structure parts (such as spars, ribs, wing covers, longerons, and frames) to obtain revised complexity factors for the advanced technology involved.

f. The evaluation of the impact on tooling factors, nonrecurring cost factors, component assembly and learning curve slopes of the technology represented and the development of corresponding estimating factors.

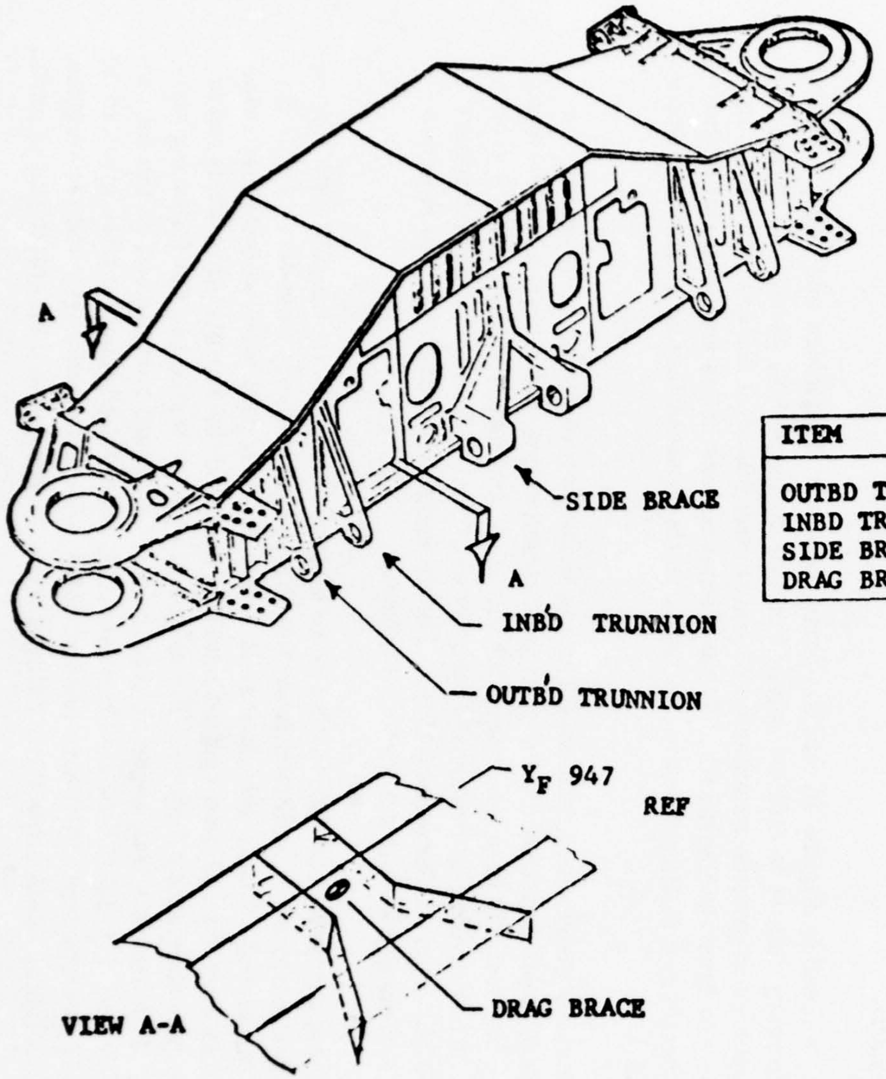
These developments involve detailed processes that are described below. The advanced structure upon which the development is based is illustrated in Figure 15. This so-called "no-box" box is described in Reference 3.

3.1.1 DATA COLLECTION. The first step in the process was the collection of data from the records of the Advanced Metallic Air Vehicle Structure program sponsored by AFFDL and conducted by the General Dynamics Fort Worth Division. Design, tooling, fabrication and material cost data and weights data were obtained. These data were in the form of detailed fact sheets for each individual part. These data were summarized by part and by assembly. The data forms are illustrated by Figures 16, 17, and 18. An individual data sheet, as illustrated by Figure 16 for the Upper Side Brace Support for the Main Landing Gear Fitting, was prepared for each part of the wing carry-through structure. These individual sheets were summarized for each assembly, as illustrated by Figure 17 for the Main Landing Gear Side Brace Fitting. The assembly summary data was in turn summarized for the wing carry-through structure, as illustrated in Figure 18. The available material, excluding the individual data sheets, is contained in Appendix B.

It will be noted in Figure 16 that the parts data is in both hours and dollars while the summary data is in dollars only. For use in this study, these data forms were restructured to provide summaries of hours (and material dollars). These summaries are furnished herewith. Table 4 summarizes hours and material dollars by assembly. A listing of hours, by part, to the revised format is given in Appendix C.

As the study progressed, the decision was made to investigate cost-weight and complexity relationships (based on type of construction and material) at the parts level. The weights data necessary for this was obtained from the AMAVS program data. It is provided by calculated weights as reported in AMAVS weight report FZW-134, dated 10 December 1974. The investigation was limited to selected parts and sought to sort out material effects.

First, subassembly and fabrication were distinguished. Then weights data for individual parts were collected from AMAVS program data. Cost-weight ratios were calculated. These data appear in Table 5. The part level weight-cost relationships were then plotted against baseline data and the results were analyzed to investigate complexity factors. These results are described in the following sections. The analysis was accomplished only for selected parts based on the following criteria: (1) Significant cost involved, (2) Priority of consideration given to 10 N_i steel and titanium, (3) Parts deemed most relevant as analogs, and (4) Weights data available. Reflecting this, Table 5 does not comprise a complete list of parts.



ITEM	X_F	Y_F	Z_F
OUTBD TRUNNION	95.5	1000	1.0
INBD TRUNNION	72.0	1000	1.0
SIDE BRACE	23.0	1000	1.0
DRAG BRACE	56.0	947.0	-4.5

Figure 15. Main Landing Gear Fitting Geometry.

PRELIMINARY COST ESTIMATE
BASIC METAL PROCESSING

PART NO. X7223924 - 7/8 NEXT ASSEMBLY X7223920 - 1/2

NAME FTG, MLG - SIDE BRACE SUPPORT, UPPR REQ. PER A/C 1/1

MATERIAL 6-4 Ti (COST $ 3.43 /LBS.) PROD. QTY. 1

MANUFACTURING PROCESS MACH FROM PLATE METHOD NO. ACTUAL

ITEM / DETAILS OF COST	TD	TP&E	MATERIAL & O.C.		HOURS FAB.	HOURS TOOLS
MATERIAL MAKE 2 PCS FROM 1 PLATE				Q.A.		
7.5 X 21.85 X 27 X .163 X 1/2 X 1.67 SF =	—					
1204.42 # X 3.43 X 1.17 CF X 1 S/S =			4,833.			
FORMING						
TP&E		168				
WELDING						
MAP A5-1 (28.4 X 1/3)					9.5	
MACHINING DUPR (-7) M/F	—		$50.	5.1	304.2	40.
(-8) (CLOSED 333)				4.6	261.9	
MAP A5-1-1 (-7) (M-333)					47.2	
A5-1-2 (-8) (M-333)					28.6	
OTHER						
Chem. Clean (DEPT 39) -7					6.2	
-8					1.4	
TOTAL		168	50.	9.7	659.0	40

RECAPITULATION 7 - 7

PART FAB.	AMOUNT	TOOLING	AMOUNT
MATERIAL		MATERIAL	$ 50.
FAB. 659 HRS. @ $13.77	9074.43	T.P.& E. 168 HRS @ $16.59	2787.
Q.A. 9.7 HRS. @ $15.59	151.22	T.D. HRS @ $16.59	—
668.7 TOTAL FAB	9225.65	T.M. 40. HRS @ $14.54	582.
MAP =	85.3	T.I. 10.4 HRS @ $15.59	162.
(-7) =	315.5	COMP. HRS @ $925.00	—
(-8) =	267.9	TOTAL - TOOLING	$ 3581.
	668.7		

Figure 16. Part Cost Data Sheet.

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

PART NO. X7223920 - 1/2
MLG SIDE BRACE FITTING
PROJECT AMAVS

DATE
BY J.L.M.
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PART NO.	LH	RH	MC	FMC	MAT	FAB	O.C.	TOOLS
3920-1/2	1	1	TI	PMW	NA	11,759		10,883
3921-7/8	1	1	TI	PM	3,167	7,758		3,309
3922-7/8	1	1	TI	PM	866	1,997		597
3923-7/8	1	1	TI	PM	3,419	5,438		2,423
3924-7/8	1	1	TI	PM	4,833	9225		3,581
TOTAL					12,285	36,177		20,793

Figure 17. Assembly Summary Data.

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224001
[redacted] WING CARRYTHRU STRUCTURE
AMAVS

JLM
1 1

PART NO.	NAME	MATERIAL	FACTORY	O. C.	TOOLS	TOTALS
4001	WCTS ASSEMBLY	$ 30,000	$ 165,670	$	$ 185,456	$ 381,126
3920	MLG SIDE BRACE	12,285	36,177		20,793	69,255
3930	XF 70 TRUNNION	9,058	15,494		12,743	37,295
3931	XF 95.5 TRUNNION	6,563	8,368		7,588	22,519
3941	MLG DRAG FTG.	9,572	18,334	13,623	14,729	56,258
3950	WING SWEEP FTG.	20,991	25,518		26,412	72,921
4006	PIVOT LUG RIB	1,403	1,650		1,432	4,485
4010	UPPER COVER	82,908	76,067		79,113	238,095
4030	OUTBD RIB	28,116	38,472		26,328	92,916
4060	BULKHEAD YF 992	63,138	69,451		75,478	208,067
4080	BULKHEAD YF 932	67,415	78,810		67,227	213,452
4110	CENTERLINE RIB	5501	14,585		19,159	39,245
4120	XF 39 RIB	11,639	25,451		14,683	51,773
4130	XF 84 RIB	4,901	9,130		16,737	30,768
4160	LOWER FAIRING	552	7,945		3,682	12,170
4170	LOWER PLATE	109,448	53,733		155,593	318,774
		$ 463,490	$ 644,855	$ 13,623	$ 727,153	$ 1,849,121

Figure 18. Wing Carry-through Structure Summary.

Table 4. Hours and Material Dollars by Subassembly.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Tool Plng.	Tool Design	N/CP	Tool Mfg.	Fabri-cation	Tooling
4001	WCTS Assembly	598	11,438.	524.	3119.7	2447.		4691.6	$ 30,000.	$ 5,867.
3920	MLG Side Brace	189	2493.6	117.6	661.	105.6		406.9	12,285.	508.
3930	X_F 70 Trunnion	170	1081.4	38.7	[illegible]		326.8	64.8	9,058.	97.
3931	X_F 95.5 Trunnion	107	594.8	11.4	153.		244.6		6,563.	
3941	MLG Drag FTG	170	1244.7	76.6	584.	42.6		218.7	9,572.	265.
3950	Wing Sweep FTG	365	1794.1	52.2	467.2	174.6	366.		20,991.	517.
4006	Pivot Lug Rib	70	106.9	11.4	30.			47.1	1,403.	59.
4010	Upper Cover	2216	5113.	363.1	1241.	377.7	1095.4	1544.2	82,908.	1311.
4030	Outbd Rib	493	2667.9	111.3	693.	147.2	157.7	471.9	28,116.	589.
4060	Bulkhead Y_F 992	1011	4550.2	436.0	1272.5	286.3	1075.8	1364.5	63,138.	1700.
4080	Bulkhead Y_F 932	1200	5279.5	392.2	1441.1	230.2	796.4	1142.1	67,415.	1438.
4110	Centerline Rib	189	937.4	107.6	266.7	58.5	328.	357.1	5,501.	546.
4120	X_F 39 Rib	378	1712.1	120.2	468.6	59.		239.6	11,639.	373.
4130	X_F 84 Rib	239	626.	32.7	166.8	.2	676.6		4,901.	
4160	Lower Fairing	37	516.3	54.0	144.5			42.9	552.	56.
4170	Lower Plate	3147	3641.8	230.1	1573.3	1281.4	2115.3	3264.5	109,448.	3505.
	TOTALS	10579	43,797.7	2679.1	12565.4	5190.3	7182.6	14269.7	$463,490.	$16,831.

Table 5. Labor and Material by Part.

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs: Subassembly	Fabrication and QA Hrs: Detail Fabr.	Fabrication and QA Hrs: Hrs./Lb.	Material: Dollars	Material: $/Lb.
4166-7/8	Web	Shear & Route	Al	11		15.5	1.4	18.	2.
4166-9, 11 13,15	Stiffener	Formed	Al	1		27.4	27.4	1.	1.
4164-7/8	Support	Machined	Al	9		62.8		132.	
4167-7/8 9/10	Support	Formed	Al	25		54.6		33.	
4168-7/8 9/15	Stiffener	Formed	Al	6		66.2		2.	
4169-11/ 12, 13/14	Clip	Formed	Al	2		47.8		3.	
						370.4	10.0	$403.	$ 10.89
4010	Upper Cover Assembly			(2216)					
4011-7/8	Pivot Lug - Upper	Machined	Ti	1629		2030.7	1.3	$61,004.	$ 37.
4013-7/8	Beam, Supt-Upper, Cover	Machined	Ti	42		599.1	14.2	3,964.	94.
4013-9/10	Beam, Supt-Upper, Cover	Machined	Ti	42		552.2	13.1	4,052.	96.
4014-7	Stiffener, Upper, Cover	Machined	Ti	14		125.1	9.0	1,528.	109.
4014-9/10	Stiffener, Upper, Cover	Machined	Ti	7		82.9	12.1	903.	129.
4014-11/ 12	Stiffener, Upper, Cover	Machined	Ti	7		97.7	13.7	531.	76.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs Subas-sembly	Fabrication and QA Hrs Detail Fabr.	Fabrication and QA Hrs Hrs./Lb.	Material Dollars	Material $/Lb.
4170-1	Lower Plate and Lug Assy.			(3147)					
4172-1/2	Panel, Lower - X_F39 to X_F84 Assy	Bonded	Ti	188	239.6		1.3	$ 98.	$ .5
4172-7/8	Skin-Panel, Lower, X_F39 to X_F84	Machined	Ti	160		231.4	1.4	5,711.	36.
4173-1	Panel-Web, Lower, Plate-Center	Bonded	Ti and Al	178			1.0	368.	2.
4173-7	Skin-Web, Lower, Plate-Center	Machined	Ti	124		222.	1.8	6,049.	49.
4174-7/8	Beam, Supt-Lower Plate, X_F 98.86	Machined	Al	35		125.6	3.6	675.	19.
4175-7	Pivot Lug, Lower	Machined	10 Ni s	2438		1489.5	.6	83,345.	34.
4176-7/8 9/10	Reinforcement-Pivot Lug, Lower	Machined	10 Ni s	303		499.5	1.6	-	-
4050-7/8	FTG, Lwr. Longeron Attach.	Machined	Al	35		131.5	3.8	313.	9.
4181-7/8	Beam Y_F 947 - MLG Brace	Machine	Ti	155		531.7	3.4	10,591.	68.
						3231.2	1.2	$107,150.	$34.05
4160	Lower Fairing Assembly			(37)					
4162-11/12	Flange	Formed	Ti	4		35.1	8.8	$ 118.	$30.
4162-25/26	Flange	Formed	Ti	.5		15.1	30.	12.	24.
4162-29/30	Flange	Formed	Ti	3.4		45.9	13.5	84.	25.
4166-1/2	Web, Lower Fairing, Assy	Rivet	Al	12	47.9		4.	-	-

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subas-sembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
4015-7/8	Splice Strap, Upr. Cover, $X_F 84$ to	Machined	Ti	2.		77.8	38.9	465.	232.
4150-1	Skin Panel, Upr, Center	Bonded Assy	Al	144.	64.8		.5		
4150-35	Skin	Route	Al	6		5.9	1.1	9.	1.5
4150-7	Skin	Machined	Al	94		34.3	.4	310.	3.
4150-9	Skin	Route	Al	5		8.8	1.8	7.	1.
4150-11, 31	Edge Members	Form & Trim	Al	2.4		38.9	16.1	41.	17.
4151-1/2	Skin Panel, Upr. Sur. X_{F39} to $X_F 84$	Bond	Al	237.	143.		.6	264.	1.1
4151-7/8	Skin Panel, Upr. Sur.	Machined	Al	157		177.7	1.1	424.	2.7
4151-9, 11, 13	Skin	Route	Al	15		47.1	3.1	22.	1.5
4151-15 to 54	Edge Member, Panel	Form & Trim	Al	6		154.2	25.4	35.	6.
4151-31 to 36	Core, Upr. Panel, $X_F 39$ to $X_F 84$	Fabrication	Al	46		109.8	2.4	551.	12
4155-7/8	Ftg, Longeron Attach-Upper ±	Machined	Al	40		100.	2.5	442.	11.
4157-7/8 9/10	Supt Fairing, upper cover	Machined	Ti	35		579.1	16.5	6,913.	198.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subassembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
4159-7/8 9/10	Beam, Skin-Upper Panel	Machined	Al	30.		117.7	3.9	760.	25.
						4939.0	2.2	$82,225.	$37.11
4080-1	Forward (Y_F 932) Blkd			(1200)					
4082-1/2	Bulkhead Panel Assembly	Adhesive Bonded	Al	161	266.7		1.7	$ 430.	3.
4082-7/8	Skin	Machined	Al	110		126.8	1.2	340.	3.
4082-11/12	Core	Fabricated	PO22-1C	27		17.1	.6	187.	7.
4083-1/2	Blkd Panel Assy, Outb'd	Adhesive Bonded	Ti	218	192.1		.9	494.	2.
4083-7/8	Skin	Machined	Ti	196		214.	1.1	5,016.	26.
4084-7	Stiffener	Machined	Ti	44		535.6	12.2	4,722.	107.
4085-7/8	Gusset	Machined	10 Ni St	29		120.8	4.2	1,361.	47.
4086-11/12-13/14	Gusset	Machined	Ti	19		182.2	9.6	1,023.	54.
4087-7	Splice	Machined	10 Ni St	10		77.3	7.7	1,342	134.
4087-9	Splice	Machined	10 Ni St	5		29.5	5.9	237	47.
4088-7/8	Support	Machined	Ti	19		152.5	8.	1,612.	85.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subassembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
4090-7/8	Bulkhead Segment	Machined	10 Ni St	604		1037.4	1.7	-	-
4091-1/2	Bulkhead Segment	Weld-GTA	10 Ni St	1503	240.7		.2	-	-
4091-7/8	Web Assy, Lower, Weldment	Weld-GTA	10 Ni St	768	188.7		.24	-	-
4093-7/8	Cap, Lower	Machined	10 Ni St	230		222.4	1.	$11,871.	52.
4095-7/8	Web	Machined	10 Ni St	538		159.2	.3	7,671.	14.
4091-9	Cap, Upper	EB Weld	10 Ni St	632	408.6		.6	-	-
4092-7	Cap, Upper - Inb'd	Machined	10 Ni St	336		545.9	1.6	15,575.	46.
4094-7	Cap, Upper - Outb'd	Machined	10 Ni St	296		249.0	.8	7,686	26.
4096-7	Cap, Upper - Splice	Machined	10 Ni St	72		301.7	4.2	5,641	78.
4098-7/8	Fitting	Machined	Ti	6		80.9	13.5	658.	110.
4098-9/10	Support	Machined	Ti	5		117.7	23.5	519.	104.
						4170.0	3.6	$67,415	$56.18
4060	Aft Bulkhead (Y_F 992)			(1011)					
4061-1	Web, Assy	Adhesive Bonding		292	209.5		.7	$ 528.	$ 2.
4061-7	Skin	Machined	Ti	252		412.4	1.6	7,778.	31.
4062-1	Cover, Assy	Bonded		13	66.4		4.9	47.	4.
4067-7/8	Stiffener	Machined	Ti	10		212.1	21.2	1,991.	199.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subas-sembly	Detail Fabr.	Hrs./ Lb.	Dollars	$/Lb.
4068-7/8	Flange	Machined	Ti	10		124.2	6.7	$ 1,798.	$ 100.
4070-7/8	Bulkhead Segment	Machined	10 Ni St	654	8[illegible]1.3		1.3	-	-
4071-1/2	Bulkhead Segment	Welded	10 Ni St	929	210.8		.23	-	-
4071-7/8	Web Assy Weldment	Welded	10 Ni St	291	315.		1.1	-	-
4073-7/8	Cap, Lower	Machined	10 Ni St	142		226.5	1.6	12,766.	90.
4075-7/8	Web, Bulkhead, Outbd	Machined	10 Ni St	149		172.	1.2	7,810.	52.
4071-9	Bulkhead Segment	EB Weld	10 Ni St	156	218.3		1.4	-	-
4072-7	Cap, Upper	Machined	10 Ni St	94		483.4	5.1	18,524.	197.
4074-7	Cap, Upper, Outbd	Machined	10 Ni St	62		293.1	4.7	6,117.	99.
4076-7	Cap, Upper, Center	Machined	10 Ni St	42		190.	4.5	2,925.	70.
4078-7/8	Fitting	Machined	Ti	5		147.7	29.4	729.	146.
4078-9/10	Fitting	Machined	Ti	4		136.4	34.	582.	146.
						2397.8	2.5	$63,138.	$ 62.45
4110	Centerline Rib			(189)					
4111-1	Rib Assembly	Bonded		122	108.9		.9	$ 337.	$ 3.
4111-7/8	Skin	Route & Mach	Al	70		75	1.1	115.	2.
4111-9,23	Core	Fabricated	PO22-1D	5		25.3	5.	183.	37.
4112-7/9	Edge Member	Machined	Al	30		109.9	3.7	1,130.	38.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subassembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
4113-9/10	Edge Member	Machined	Al	8.5		106.5	12.5	153.	18.
4114-7/8	Beam	Machined	Al	27		145.2	5.4	$ 1,104.	41.
4114-9	Beam	Machined	Al	21		131.1	6.2	641.	31.
4118-7/8	Longeron	Machined	Al	39		135.8	3.5	1,083.	28.
4119-7	Fitting	Machined	Ti	2		30.3	15.1	219	109.
						759.1	4.2	5,501	$ 29.11
4120	X_F Rib			(378)					
4121-1/2	Panel, Rib, X_F 39	Bonded	Al	177	268.1		1.5	$ 322.	2.
4121-7/8	Skin - Panel, Rib, X_F39	Machined	Al	100		105.8	1.1	510.	5.
4122-7/8	Beam, Lower, Rib, X_F39	Machined	Al	51		173.6	3.4	919.	18.
4124-9/10	Flange, Rib-Forward, X_F39	Machined	Ti	26		410.3	15.8	2,098.	81.
4125-9/10	Flange, Rib, Aft, X_F39	Machined	Al	12		135.9	11.3	201.	17.
4126-7/8	Splice - Lower, X_F39	Machined	Ti	25		320.3	12.8	5,296.	212.
						1145.9	3.9	$11,639.	$ 30.79
4030-1/2	Closure Rib Installation	Bolted Assy	Al, Ti	(586)	168.4		.3		
4031-7/8	Web	Machined	Ti	232		268.4	1.2	$ 4,889.	21.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subas-sembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
4032-7/8	Support	Machined	Ti	55		307.4	5.6	5,164.	94.
4032-9/10	Support	Machined	Ti	60		377.2	6.3	4,810.	80.
4033-7/8 9/10	Support	Machined	Ti	45		433.	9.6	5,173.	115.
4034-7/8	Support	Machined	Ti	25		407.9	16.3	2,874.	115.
4034-9/10	Support	Machined	Ti	7		91.8	13.1	938.	134.
4034-11/12	Support	Machined	Ti	11		137.8	12.5	1,079.	98.
4035-7/8	Support	Machined	Ti	10		132.8	13.3	1,122.	112.
4035-9	Support, Closure Rib	Machined	Ti	5		51.9	10.4	415.	83.
4036-7,9	Stiffener	Machined	Al	27		107.2	4.0	276.	10.
4036-11, 13,15	Stiffener, Closure Rib	Machined	Al	33		180.9	5.5	962.	29.
4037-1/2	FTG, Shear Lüng (& Bushing)	Machined	Ti	7		114.5	16.5	414.	59
						2610.8	4.5	$28,116.	$ 47.98
4130	X_F 84 Rib			(239)					
4131-7/8	Rib	Machined	Al	237		520.1	2.2	$4,035.	$ 17.
4132-7	Flange	Machined	Al	12		32.9	2.7	243.	20.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subassembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
4133-7/8	Plate, Splice	Machined	Ti	14		101.7	7.3	613.	44.
						654.7	2.7	$ 4,901.	$ 20.50
3920-1/2	FTG, MLG Side Brace	Weld and Machine	Ti	(186)	843.9		4.5		
3921-7/8	FTG, MLG Side Brace Spt, Outb'd	Machined	Ti	79		562.	7.1	3,167.	40.
3922-7/8	Web, MLG Side Brace Spt	Machined	Ti	7		144.3	20.6	866.	124.
3923-7/8	FTG, MLG Side Brace Spt, Inb'd	Machined	Ti	45		392.8	8.7	3,419.	76.
3924-7/8	FTG, MLG Side Brace Spt, Upper	Machined	Ti	55		688.7	12.2	4,833.	88.
						1787.8	9.6	$12,285.	$ 66.05
3930-7/8	Trunnion, MLG, X_F72	Machined	Ti	140		895.1	6.4	$ 8,334.	$ 60.
3932-7	Cap, Trunnion, MLG, X_F72	Machined	Ti	15		225.	15.	724.	48.
3931-7/8	Trunnion, MLG, X_F 95.5	Machined	Ti	98		606.2	6.2	6,563.	67.

Table 5. Labor and Material by Part (Continued).

Part No.	PART NAME	Type of Construction	Type of Material	Wt. (Lbs.)	Fabrication and QA Hrs			Material	
					Subassembly	Detail Fabr.	Hrs./Lb.	Dollars	$/Lb.
3941-1/2	Drag FTG, MLG, Assy	Weld and Machine	Ti	(171)	217.5		1.3		
3942-9/10	Drag FTG, MLG, Inbd Beam	Machined	Ti	82		480.6	5.9	$ 4,038.	$ 49.
3943-9/10	Drag FTG, MLG, Outbd Beam	Machined	Ti	66		381.1	5.8	3,333.	51.
3944-11/13	Beam Extension, Drag FTG, MLG	Machined	Ti	14		124.8	8.9	1,249.	89.
3945-9/10	Drag FTG, MLG, Splice	Machined	Ti	13		116.9	9.	952.	73.
						1103.4	6.5	$ 9,572	$ 55.98
3950-7/8	Wing Sweep Act. Sub Assy	Fastener Assembly	Ti & Al	366	288.7		8.		
3901-9/11	FTG, Wing Sweep Act. Spt.	Machined	Ti	303		1482.9	4.9	$18,954.	$ 63.
4006-7/8	Rib, Pivot Lug Y_F 944.15	Machined	Al	70		118.3	1.7	$ 1,403.	$ 20.
4001	WCTS Assembly	Final Assy		598	11,962		20.	$30,000.	$ 50.

3.1.2 COST-WEIGHT RELATIONSHIPS. A preliminary analysis was made of the parametric relationships between weight and cost for the assembly level data. These relationships are shown in Table 6. In addition, certain measures of central tendency were computed for selected relationships: the arithmetic mean, the standard deviation and the coefficient of variation, for fabrication hours per pound (including quality assurance), tool manufacturing hours per pound, fabrication material dollars per pound, and tool planning hours per pound.

By inspection of the data in this table, it can be observed that several examples of machined titanium occur. The results of this further analysis are given in Table 7. These results are used for machined titanium structure after being related to baseline values.

3.1.3 ESTIMATING FACTOR DEVELOPMENT. In the present trade study estimating method, the wing carry-through structure is categorized as secondary structure at an aggregate level. Estimating factors were developed at this level based on the cost estimating relationships defined for the method. These relationships are as follows:

(1) Detail Fabrication Hours for Secondary Structure[1]

$$H_i = CB_i \, (WC_i) \, (WD_i)^{E_i}$$

where

H_i = detail fabrication hours, secondary structure

CB_i = a series of complexity factors corresponding to component type related to fabrication

WC_i = a series of reference cost per pound values for secondary structure components related to fabrication labor

WD_i = a series of weights for the secondary structure components being estimated

E_i = a series of weight scaling exponents for secondary structure components related to fabrication labor.

(1) Equation (10), Page 70, Reference 1.

Table 6. AMAVS WCTS - Assembly Level Cost Weight Relationships.

Part No.	NAME	Wt. (lbs)	Type of Construction	Type of Material	Hrs (Fab+QA) Per lb	Hrs (TM /lb)	Fab Mat'l $/lb	Hrs (TP /lb)
4001	WCTS Assembly	598	Assembly	-	20.0	7.8	$50.2	5.2
3920	MLG Side Brace	189	Machined	Ti	13.8	2.2	65.0	3.5
3930	XF to Trunnion	170	Machined	Ti	6.6	0.4	53.8	1.7
3931	XF 95.5 Trunnion	107	Machined	Ti	5.7	-	61.3	1.4
3941	MLG Drag Fitting	170	Machined	Ti	18.2	1.3	56.3	3.4
3950	Wing Sweep Fitting	365	Machined	Ti & Steel	4.0	-	57.5	1.3
4006	Pivot Lug Rib	70	Machined	Al	1.7	0.7	20.0	0.4
4010	Upper Cover	2216	Built Up	Ti, Al, 10Ni	2.5	0.7	37.4	0.6
4030	Outbd Rib	493	Machined	Ti	5.6	0.9	57.0	1.4
4060	Bulkhead YF 992	1011	Built Up	Ti, Al, 10Ni	4.9	1.4	62.5	1.3
4080	Bulkhead YF 932	1200	Built-Up	Ti, Al, 10Ni	4.7	0.9	56.2	1.2
4110	Centerline Rib	189	Built-Up	Ti, Al	5.5	1.9	29.1	1.4
4120	X_F 39 Rib	378	Built-Up	Ti, Al	4.8	0.6	30.8	1.2
4130	X_F 84 Rib	239	Machined	Al	2.8	-	20.5	0.7
4160	Lower Fairing	37	Built-Up	Ti, Al	15.4	1.2	14.9	3.9
4170	Lower Plate	3147	Built-Up	Ti, Al, 10Ni	1.2	1.0	34.8	0.5
		10579			$\bar{X}$ = 4.5 S = 6.5 V = 144%	$\bar{X}$ = 1.3 S = 1.8 V = 138%	$\bar{X}$ = 43.8 S = 16.5 V = 37.7%	$\bar{X}$ = 1.2 S = 1.5 V = 12.5%

S = Standard Deviation

V = Coefficient of Variation: $S/\bar{X}$

Table 7. AMAVS WCTS - Machine Titanium Cost/Weight Relationships.

Part No.	NAME	Wt. (lbs)	Type of Construction	Type of Material	Hrs (Fab+QA) Per lb	Hrs (TM /lb)	Fab Mat'l $/lb)	Hrs (TP /lb)
3920	MLG Side Brace	189	Machined	Ti	13.8	2.2	65.0	3.5
3930	XF to Trunnion	170	Machined	Ti	6.6	.4	53.3	1.7
3931	XF 95.5 Trunnion	107	Machined	Ti	5.7	-	61.3	1.4
3941	MLG Drag FTG	170	Machined	Ti	18.2	1.3	56.3	3.4
4030	OUTBD Rib	493	Machined	Ti	5.6	.9	57.0	1.4
		1129			$\overline{X}$ = 10. S = 5.1 V = 51%	$\overline{X}$ = 1.2 S = .7 V = 58%	$\overline{X}$ = 58.6 S = 4.1 V = 7%	$\overline{X}$ = 2.3 S = .96 V = 42%

(2) Subassembly Hours for Secondary Structure[1]

$$H_i = CC_i\,(WF_i)\,(WD_i)^{F_i}$$

where

H_i = subassembly hours, secondary structure

CC_i = a series of complexity factors corresponding to component type related to subassembly

WF_i = a series of reference cost per pound values for secondary structure components related to fabrication labor

WD_i = the same series of weights as for detail fabrication

F_i = a series of weight scaling exponents for secondary structure components related to subassembly labor.

Estimating coefficients consist of the reference cost-per-pound terms WC_i and WF_i and the complexity factors CB_i and CC_i. The original data base for the wing carry-through structure is illustrated in Figures 19 and 20.

The wing carry-through structure had been categorized as secondary structure in the Reference 1 study largely as a matter of convenience, inasmuch as costs were not analyzed at a detailed level. In this study the wing carry-through structure is classified as primary structure and analyzed at a corresponding level of detail. The estimating technique was driven to this lower level of indenture. This development is discussed and illustrated below, based on the costing concept illustrated in Figure 21.

The concept relies on a CER that relates the definition of a given hardware element in terms of size and relative complexity of manufacture. The analysis leading to the definition of size is performed by the various design and weight synthesis programs used. Size is usually, but not always, defined in terms of weight. Complexity is defined in terms of type of material and type of construction and is symbolized by a numerical complexity factor. In the case of primary structure, the CER uses a complexity weighting according to the mix of types of construction and/or material and uses this as a multiplier of a baseline cost per pound

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(1) Equation (11), page 74, Reference 1.

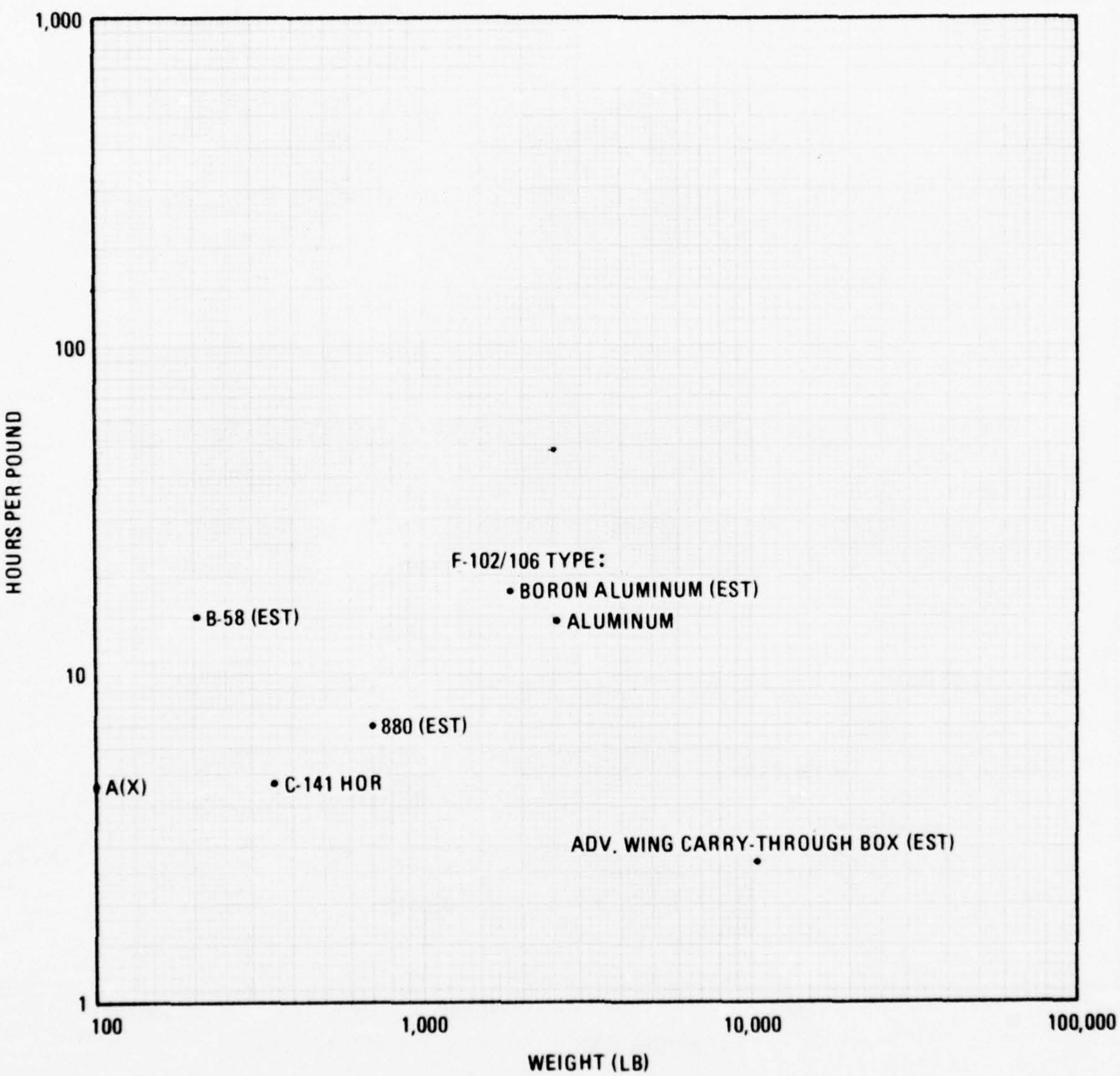

Figure 19. Wing Carry-through Box Detail Fabrication Hours Per Pound Against Weight. (Figure F-36 in Reference 1.)

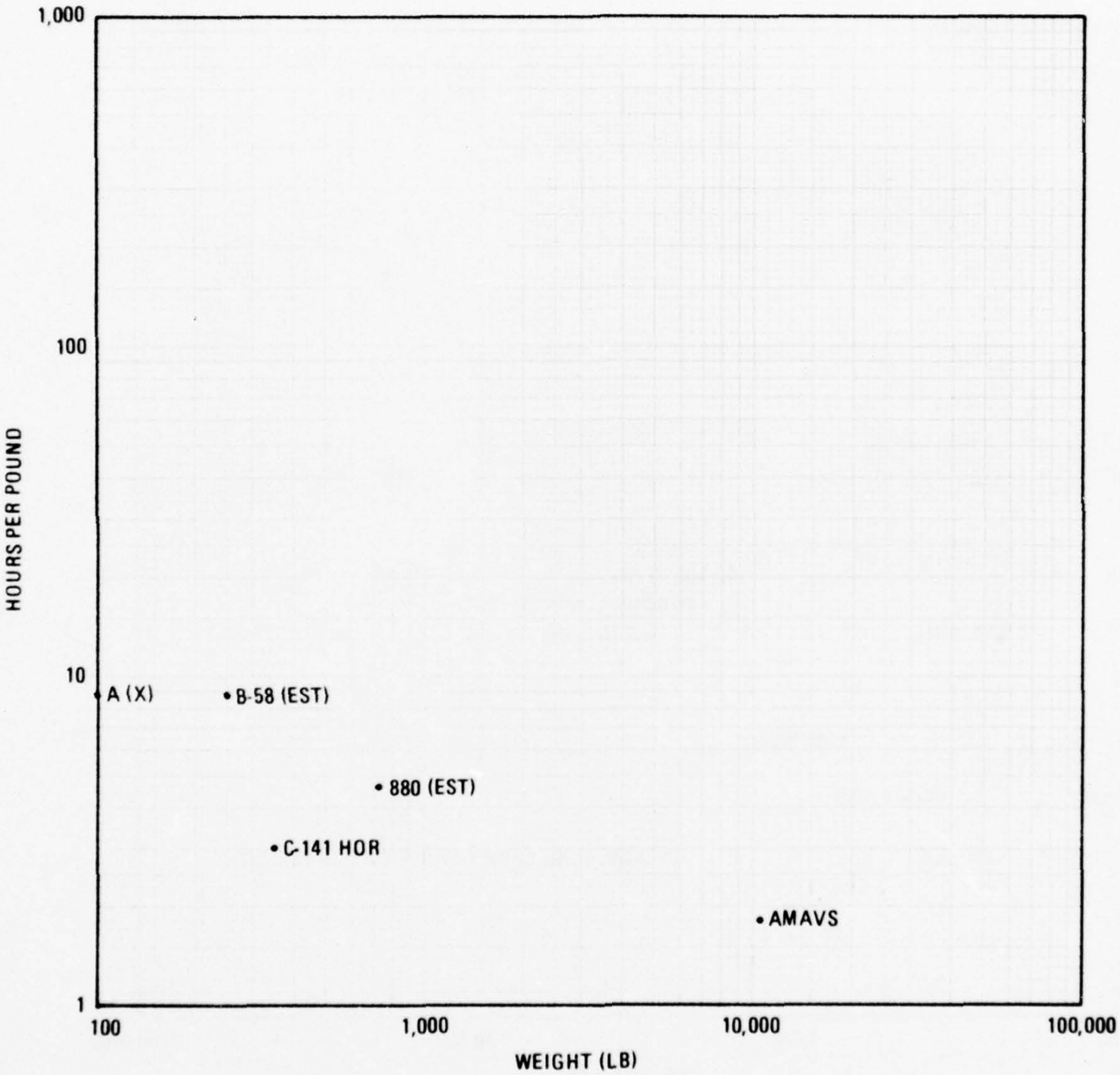

Figure 20. Wing Reaction Box Subassembly Hours Per Pound Against Weight. (Figure F-79 in Reference 1.)

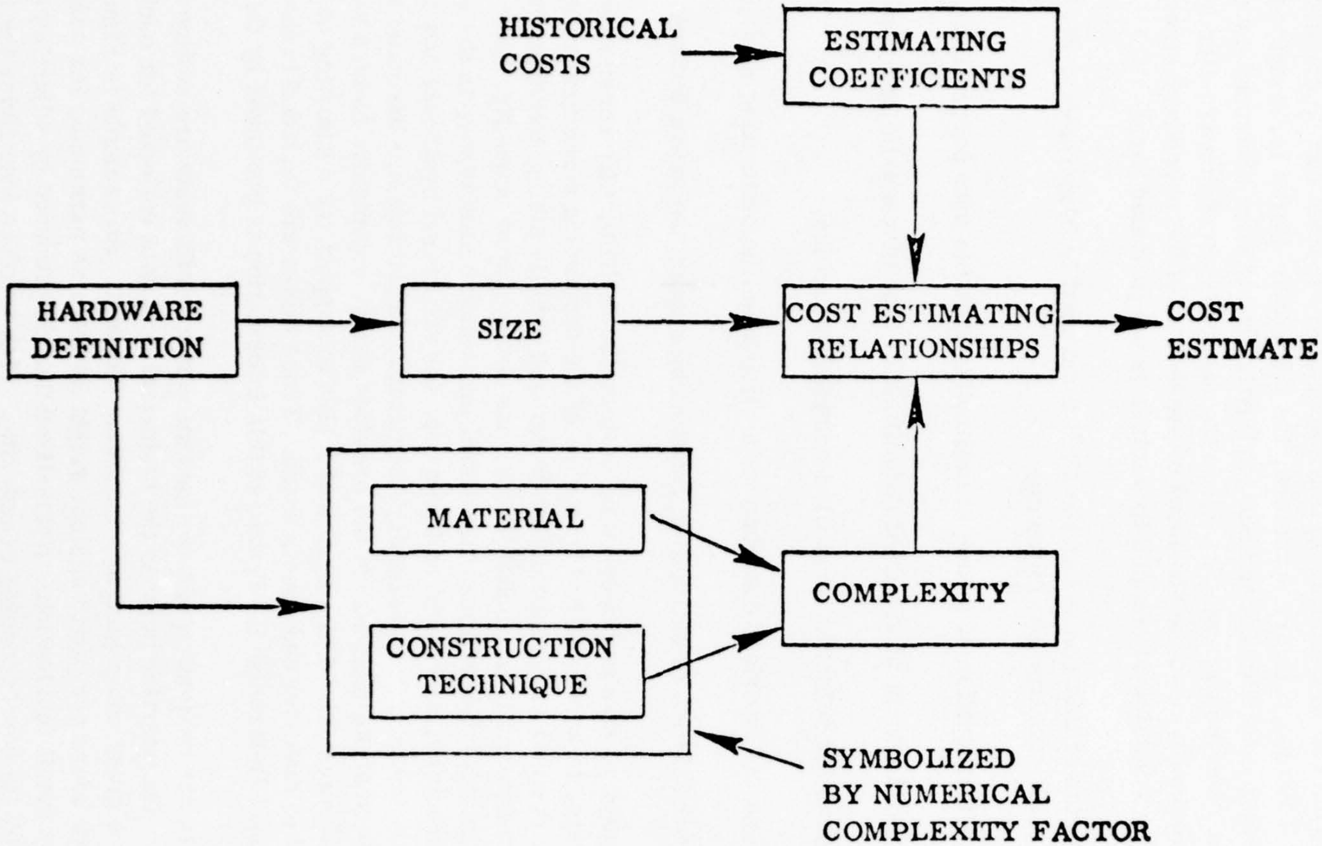

Figure 21. Costing Concept.

coefficient. It then scales this product against the weight of the component using a baseline scaling exponent. Historical cost data is used in developing the baseline cost per pound and in establishing that the scaling exponent can be considered as a constant. Thus for primary structure, the CER form allows for consideration of three different material or construction types. In the case of secondary structure, the concept remains the same but since the mix of types of construction and material does not frequently occur at the level of breakdown of the secondary structure components, the weighting of complexity factors is not provided for.

The translation of this concept to the CER form used is illustrated in Figure 22. Use of the CER requires the following:

a. The determination of means of estimating suitable size parameters.

b. The development of standard definitions of type of material and construction.

c. A means for selecting quantified complexity factors.

d. The use of historical cost data to develop baseline estimating coefficients.

e. The formulation of estimating relationships using the above factors.

The estimation of size parameters in an iterative fashion, with consideration of sizing effects, is accomplished by means of the supporting structural synthesis programs, coupled with preliminary design and vehicle sizing activities (the required parameters, i.e., model inputs, can be developed manually, however, for a point estimate.) Definitions of material and construction types, in the case of primary structure, are based on those used for structural synthesis and weight estimation. In the case of secondary structure, definitions are based on standard weight statement definitions. In the previous study, complexity factors were developed and summarized in a series of tables to support the estimating of the defined types of material and construction. These tables are included in the Estimating Handbook, Reference 1. Update of this information is continued by this study.

The steps in the derivation of baseline estimating coefficients are outlined in Figure 23. The starting point is the historical cost data collected for each type of cost for a given component of a hardware element. An example is Figure 19, which shows hours per pound against weight as the size parameter for wing carry-through box detail fabrication. Normalized data is produced by adjusting each data point by its corresponding complexity. This involves identifying the type of construction and material represented and dividing the data point by the corresponding complexity value. The effect of this process is to normalize all data

SIZE PARAMETERS

APAS PROGRAM OUTPUT
SECONDARY STRUCTURE WT. EST.
OTHER WT. ESTIMATION

COMPLEXITY FACTOR

COMPLEXITY FACTOR TABLES

BASELINE EXPONENT

HISTORICAL DATA

$$H_i = \left[\frac{\left(W_i\,CF_i + W_i\,CF_i + W_i\,CF_i\right)\left(HF_i\right)\left(WT_i\right)}{WT_i}\right]^{E_i} \times (R)$$

LABOR RATE

BASELINE ESTIMATING COEFFICIENT

HISTORICAL DATA

Figure 22. CER Form for Costing Concept.

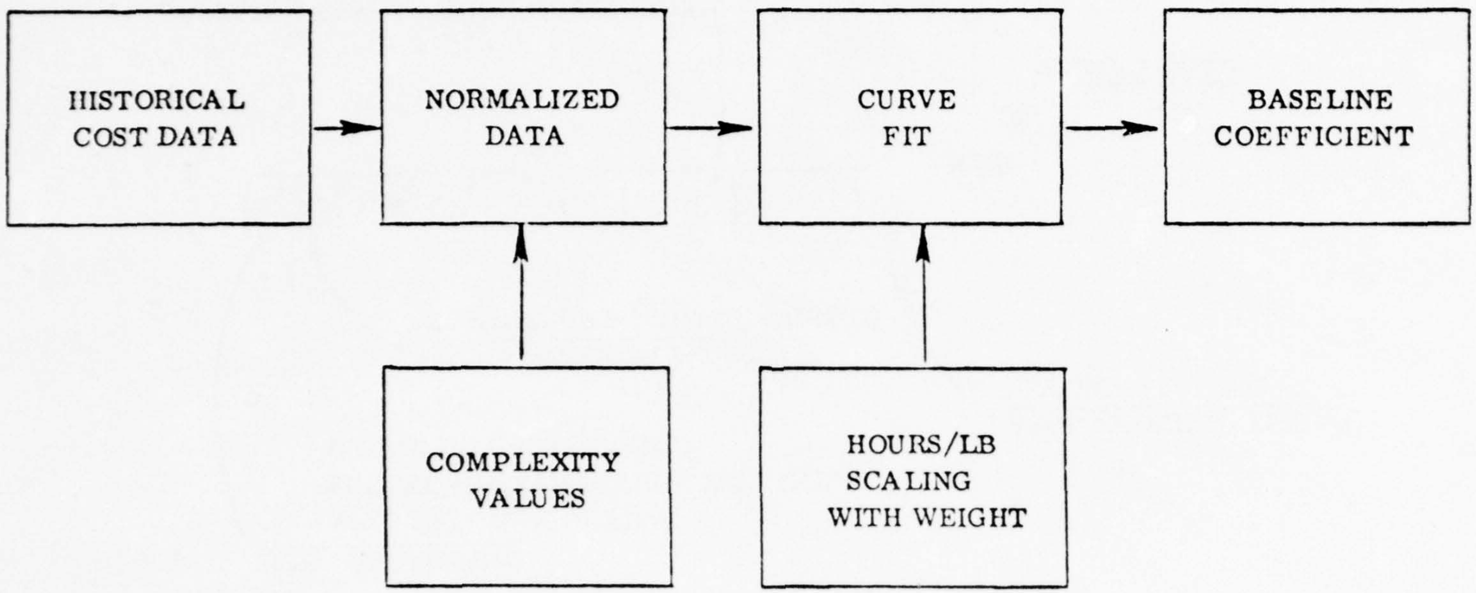

Figure 23. Derivation of Estimating Coefficients.

points to the type of construction and material to which the complexity is referenced. Applying this process to each of the data points, results in the adjustments shown in Figure 24.

The next step is the fitting of a curve to the data. This step is also illustrated in Figure 24. A basic assumption is made at this point: that the scaling of hours per pound with weight is a constant of determinable value.

The combination of the above, which in actual practice is accomplished by input to the computer program, completes the formulation of the estimating relationship.

The assembly level analysis was accomplished next. The data contained in Table 8 was used in plotting various scatter diagrams, Figures 25 through 28. These data were developed by combining the information in Table 4 and Table 5 in the following manner: Table 5 provides the breakout of subassembly and detail fabrication, excluding low cost parts. Table 4 gives the total value for manufacturing and quality assurance hours. These are added, and detailed fabrication and subassembly hours from Table 5 (and excluding Quality Assurance) are proportionately increased to the Table 4 total. Weight data is from Table 4. The plots in Figures 27 and 28 are further analyzed to illustrate assembly level results.

Analysis of Figure 27

Based on previous observations of the relationship between cost per pound and weight, we assume a relationship of the form, $Y = ax^b$. (1)

This reduces to the log-linear form,

$$\log Y = \log a + b \log x \qquad (2)$$

The normal equations corresponding to the least squares line are

$$\sum Y = a_o N + a_1 \sum X \text{ and } \sum XY = a_o \sum X + a_1 \sum X^2$$

from which

$$a_o = \frac{(\sum Y)(\sum X^2) - (\sum X)(\sum XY)}{N\sum X^2 - (\sum X)^2} \quad \text{and}$$

$$a_1 = \frac{N\sum XY - (\sum X)(\sum Y)}{N\sum X^2 - (\sum X)^2}$$

Calling Log Y = Y and Log x = X, equation (2) can be rewritten as

$$Y = a_o + a_1 X \text{ where}$$

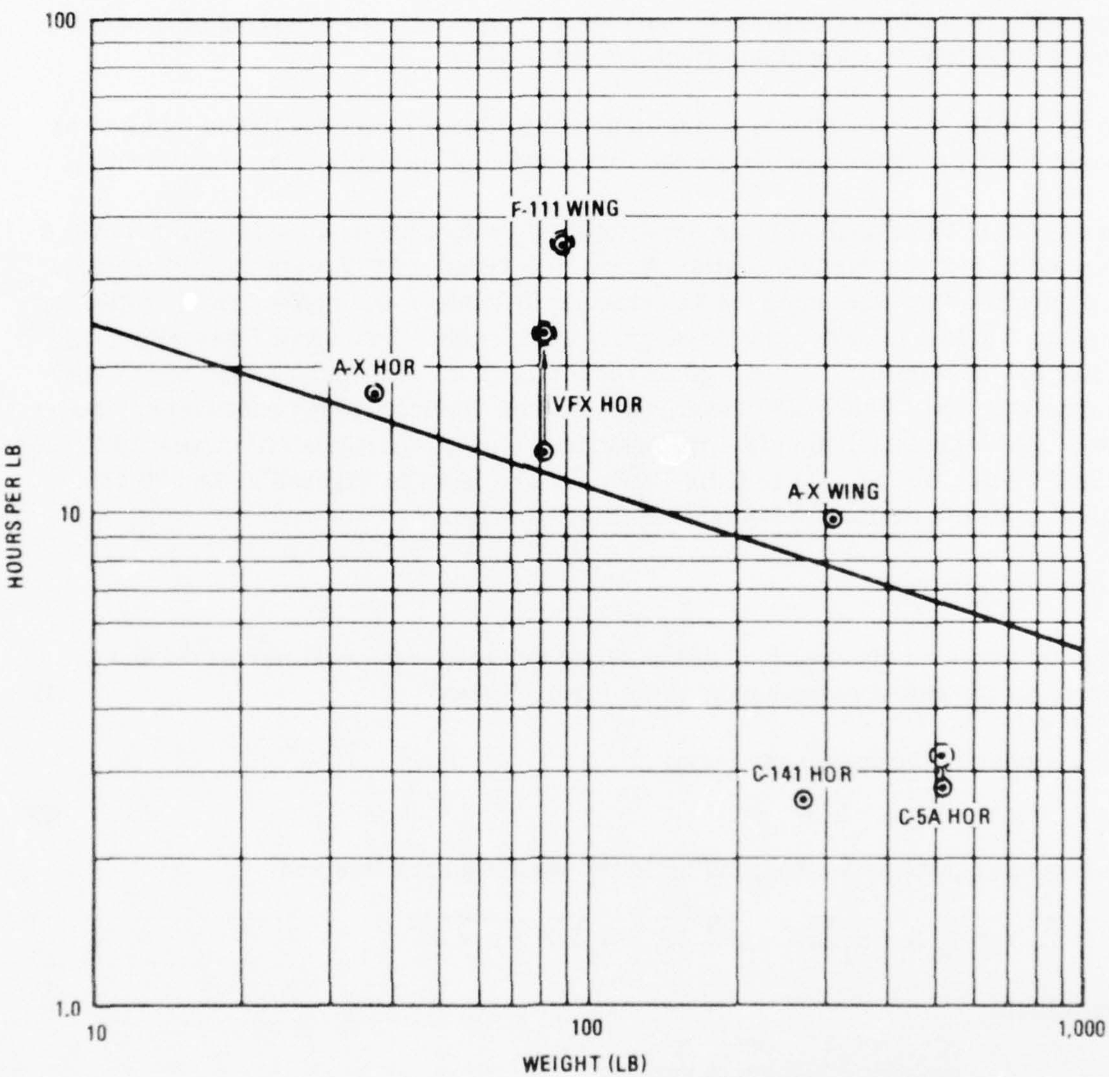

Figure 24. Normalized Data - Rib Detail Fabrication.
(Figure F-36 in Reference 1.)

Table 8. Summary of Fabrication and QA Hours Broken Down by Detail Fabrication and Subassembly.

Part No.	Table 5		Table 4	Columns (1) and (2) Adjusted to Col (3) Tot		Wt. (Lbs)	Subassembly Hours Per Pound	Detail Fabrication Hours per Pound
	Sub Assembly	Detail Fabr.	Fab Plus QA Hours	Sub Assembly	Detail Fabr.			
4001	11962.		11962.	11962.		598	(20.0)	
3920	843.9	1787.8	2611.2	836.9	1774.3	189	4.4	9.4
3930	-	1120.1	1120.1	-	1120.1	170	-	6.6
3931	-	606.2	606.2	-	606.2	107	-	5.7
3941	217.5	1103.4	1321.3	217.6	1103.7	170	1.3	6.5
3950	288.7	1482.9	1846.3	300.8	1545.5	365	.8	4.2
4006	-	118.3	118.3	-	118.3	70	-	1.7
4010	207.8	4939.0	5476.1	221.1	5255.0	2216	.1	2.4
4030	168.4	2610.8	2779.2	168.4	2610.8	493	.34	5.3
4060	1851.3	2397.8	4986.2	2172.4	2813.8	1011	2.15	2.8
4080	1296.8	4170.	5671.7	1345.4	4326.3	1200	1.1	3.6
4110	108.9	759.1	1045.0	131.1	913.9	189	.7	4.8
4120	268.1	1145.9	1832.3	347.4	1484.9	378	.9	3.9
4130	-	654.7	658.7	-	658.7	239	-	2.8
4160	47.9	370.4	570.3	65.3	505.	37	1.8	13.6
4170	417.6	3231.2	3871.9	443.1	3428.8	3147	.14	1.1
							13.73	74.4
	17678.9	26497.6	46476.8	18211.5	28265.3	10579	$\bar{Y} = 1.248$	$\bar{Y} = 4.96$

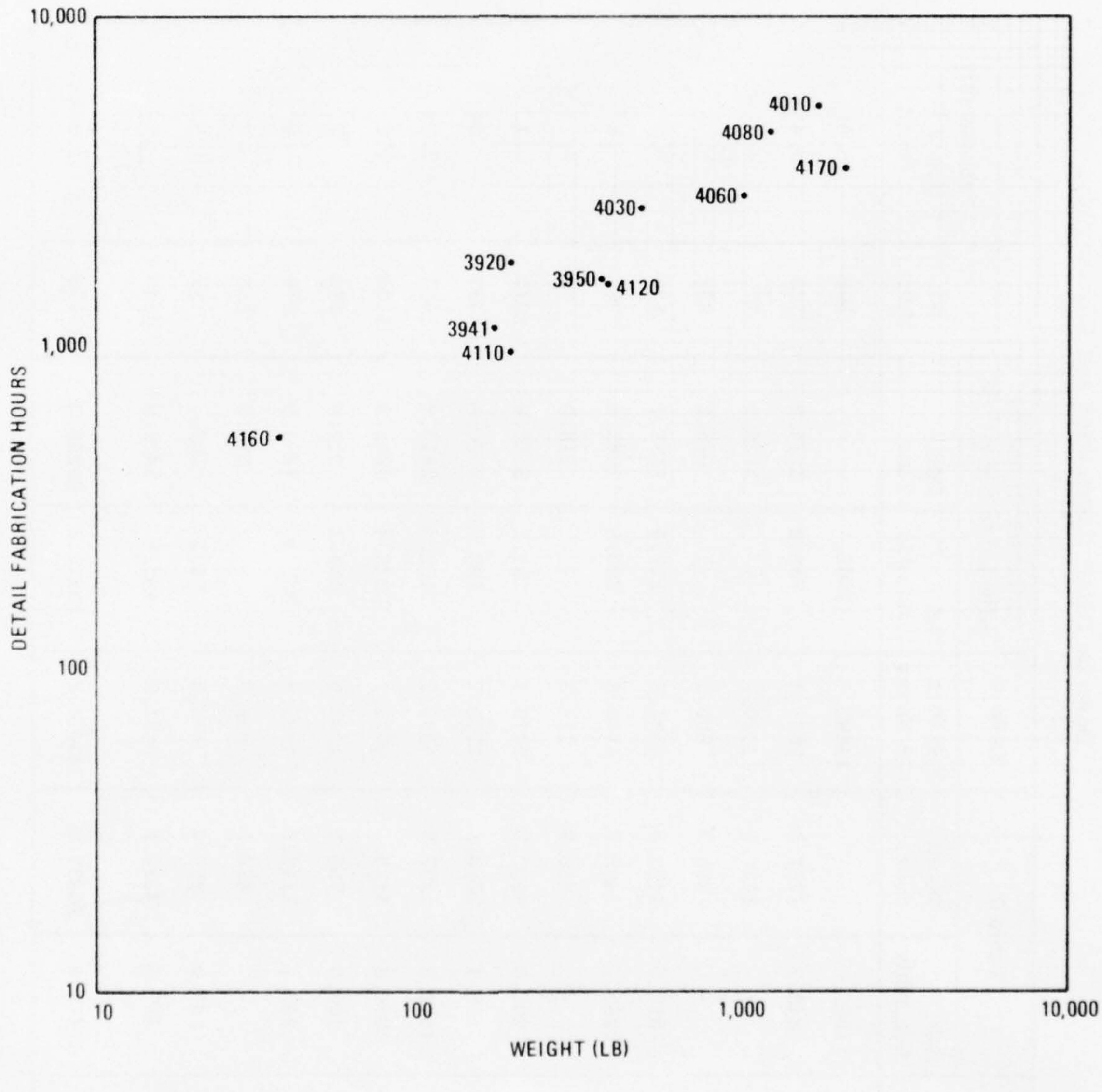

Figure 25. Wing Carry-through Box Assemblies - Detail Fabrication Hours Against Weight.

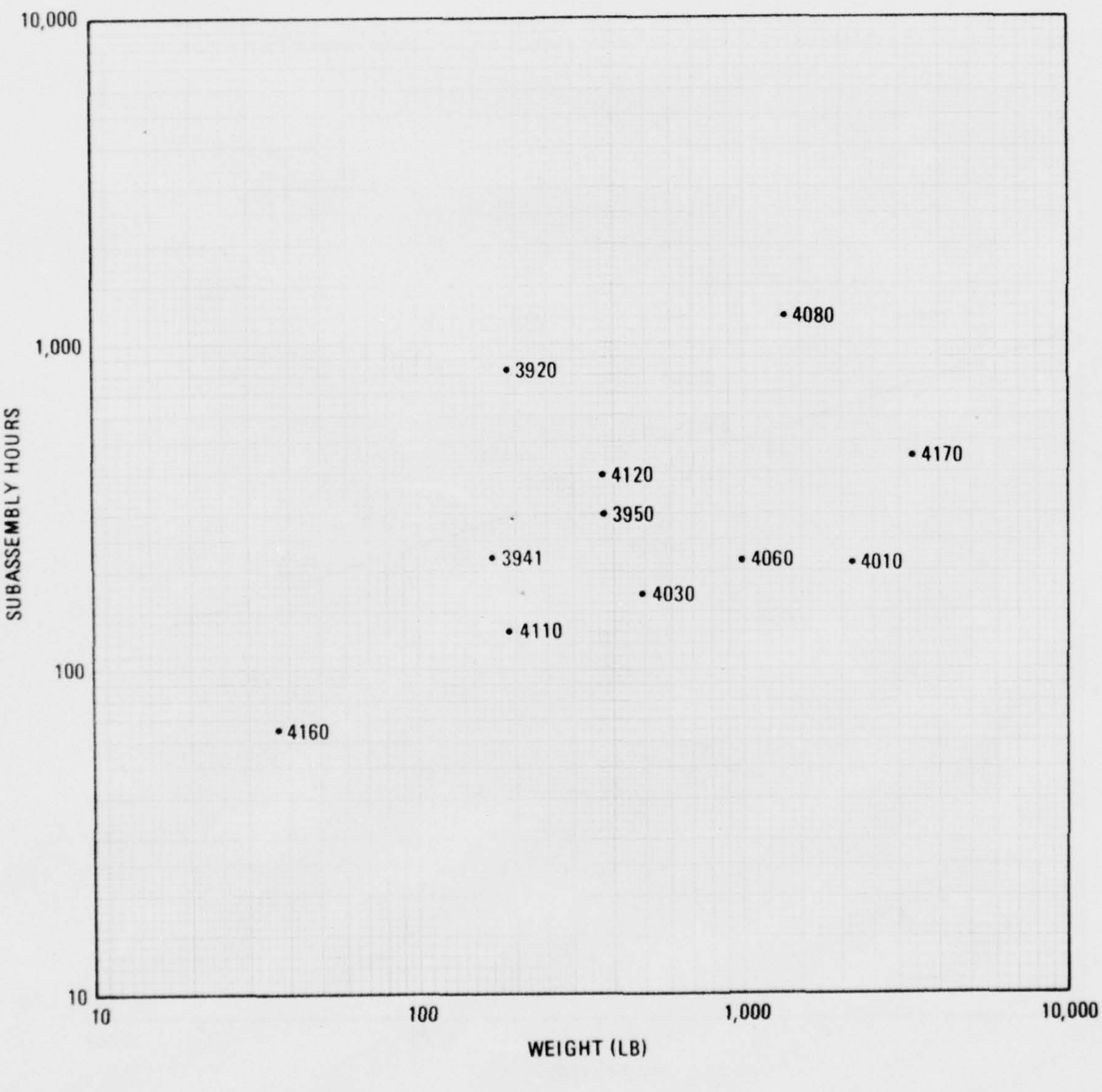

Figure 26. Wing Carry-through Box Assemblies - Subassembly Hours Against Weight.

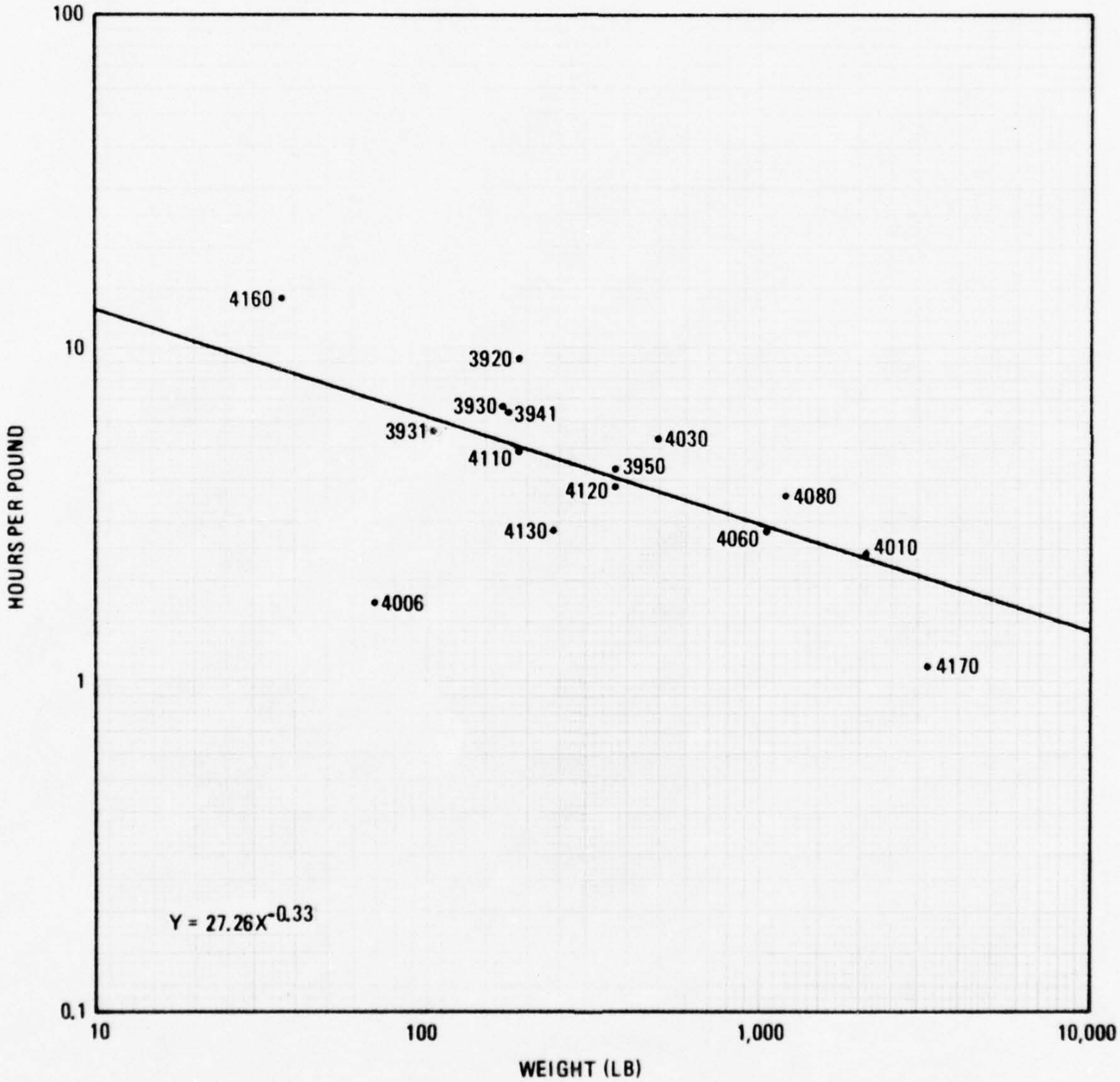

Figure 27. Wing Carry-through Box Assemblies - Detail Fabrication Hours Per Pound Against Weight.

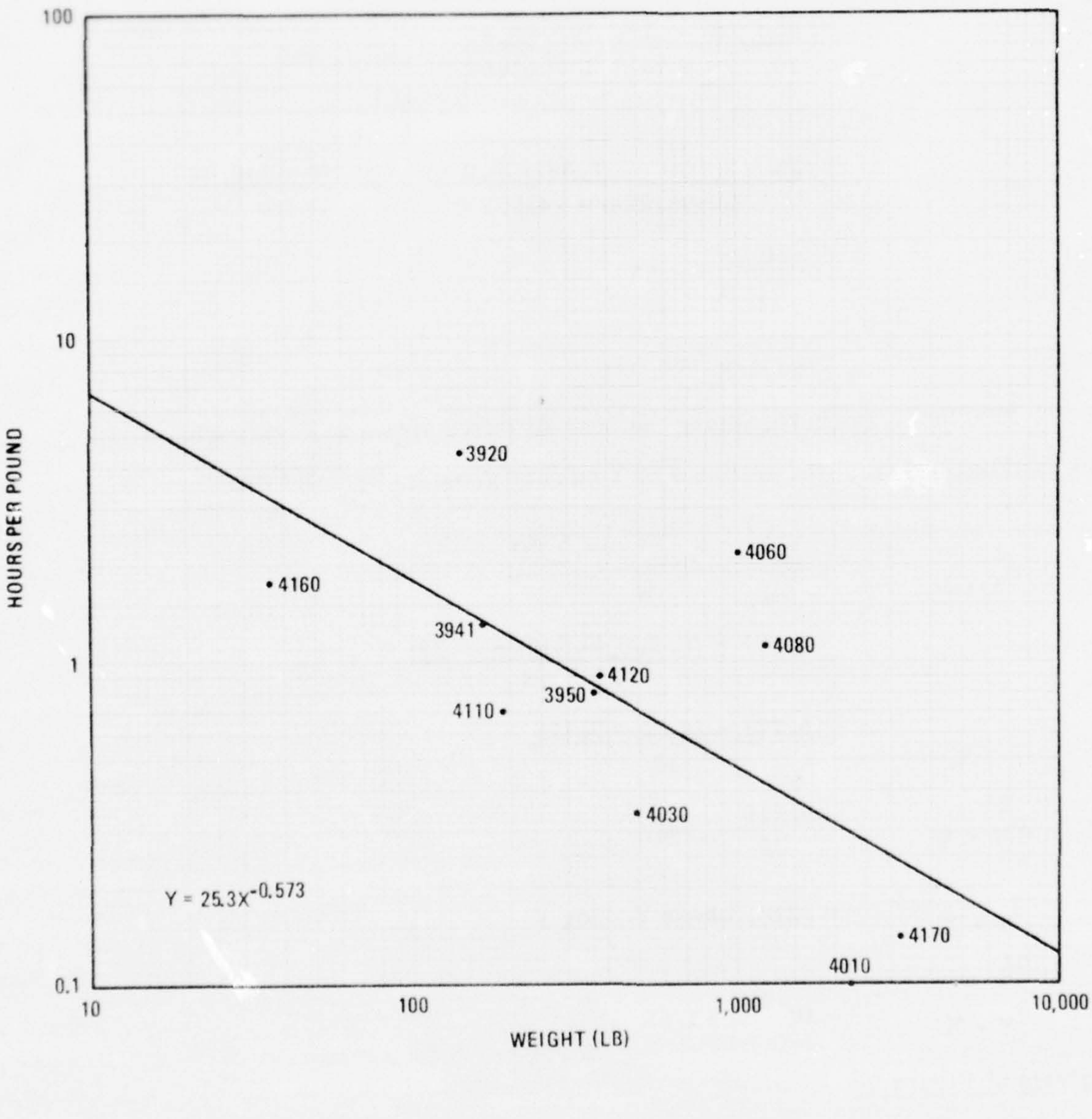

Figure 28. Wing Carry-through Box Assemblies - Subassembly Hours Per Pound Against Weight.

a_o = log a and a_1 = b. Table 9 gives the necessary detailed calculations.

Then,

$$a_o = \log a = \frac{(9.216)(98.334) - (37.591)(21.744)}{15\ (98.334) - 1413.1}$$

$$= \frac{906.246 - 817.379}{1475.01 - 1413.1} = \frac{88.87}{61.91} = 1.4355, \text{ and}$$

$$a = 27.26$$

$$a_1 = b = \frac{15\ (21.744) - (37.591)\ (9.216)}{15\ (98.334) - 1413.1} = \frac{326.16 - 346.44}{61.91}$$

$$= \frac{-20.28}{61.91} = -.33$$

and

$$Y = 27.26X^{-.33}.$$

At X = 1000 lbs., Y = 2.79, giving the best-fit curve shown in Figure 27.

The standard error of the estimate of Y on X is given by the following:

$$S^2_{Y \cdot X} = \frac{\sum Y^2 - a_o\sum Y - a_1\sum XY}{N}$$

$$= \frac{6.771 - (1.436)\ (9.216) - (-.33)\ (21.744)}{15}$$

$$= \frac{6.771 - 13.23 + 7.175}{15}$$

$$S^2_{Y \cdot X} = \frac{0.716}{15} = .0477$$

$$S_{Y \cdot X} = .218, \text{ where } Y = \log Y$$

or

$$S_{Y \cdot X} = 10^{.218} = 1.65$$

Analysis of Figure 28

Using the same method as for Figure 27, Table 10 gives detailed calculations.

Table 9. Calculation of Statistics for Detailed Fabrication.

$X = \log X$	$Y = \log Y$	Y^2	X^2	XY
2.276	0.973	0.947	5.180	2.215
2.230	0.820	0.672	4.973	1.829
2.029	0.756	0.572	4.117	1.534
2.230	0.813	0.661	4.973	1.813
2.562	0.623	0.388	6.564	1.596
1.845	0.230	0.053	3.404	0.424
3.346	0.380	0.144	11.196	1.271
2.693	0.724	0.524	7.252	1.950
3.004	0.447	0.200	9.024	1.343
3.079	0.556	0.309	9.480	1.712
2.276	0.681	0.464	5.180	1.550
2.577	0.591	0.349	6.641	1.523
2.378	0.447	0.200	5.655	1.063
1.568	1.134	1.286	2.459	1.778
3.498	0.041	0.002	12.236	0.143
$\sum X = 37.591$	$\sum Y = 9.216$	$\sum Y^2 = 6.771$	$\sum X^2 = 98.334$	$\sum XY = 21.744$

Table 10. Calculation of Statistics for Subassembly.

$X = \log X$	$Y = \log Y$	X^2	Y^2	XY
2.276	.643	5.180	.413	1.463
2.230	.114	4.973	.013	.254
2.562	.097	6.564	.009	-.249
3.346	-1.000	11.196	1.	-3.346
2.693	-.469	7.252	.220	-1.263
3.004	.332	9.024	.110	.997
3.079	.041	9.480	.0017	.126
2.276	-.155	5.180	.024	-.353
2.577	-.046	6.641	.002	-.119
1.568	.255	2.459	.065	.400
3.498	-.854	12.236	.729	-2.987
$\sum X = 29.109$	$\sum Y = -1.236$	$\sum X^2 = 80.185$	$\sum Y^2 = 2.5867$	$\sum XY = -5.077$

Then,

$$a_o = \log a = \frac{(-1.236)\ (80.185) - (29.109)\ (-5.077)}{11\ (80.185) - 847.3}$$

$$= \frac{-99.1 + (+147.8)}{552 - 847.3} = \frac{48.7}{34.7} = 1.403, \text{ and}$$

$$a = 25.3$$

$$a_1 = b = \frac{11(-5.077) - 29.109)\ (-1.236)}{34.7} = \frac{-55.847 + (+35.98)}{34.7}$$

$$= \frac{-19.87}{34.7} = .573$$

Then

$$Y = 25.3\ X^{-.573}$$

At $X = 10$, $Y = 6.76$ and

at $X = 1000$, $Y = .483$, giving the best-fit curve shown in Figure 28.

The standard error of the estimate of Y on X is

$$S^2_{Y \cdot X} = \frac{2.587 - (1.403 \times (-1.236)) - (-.573)\ (-5.077)}{11}$$

$$= \frac{2.587 + 1.734 - 2.909}{11} = .128$$

where Y = Log x.

For Y,

$$S_{Y \cdot X} = 10^{.128} = 1.343$$

The coefficient of variation (the standard error of the estimate divided by the mean value of Y) provides a measure of the usefulness of the equation for estimating Y. Values of $\overline{Y}$ are given in Table 8. The coefficient of variation for detail fabrication hours per pound is,

$$CV = \frac{SE}{\overline{Y}} = \frac{1.65}{4.96} = .33$$

The coefficient of variation for subassembly hours pound is,

$$CV = \frac{1.34}{1.25} = 1.07$$

The relative estimating value of the relationships for detail fabrication and subassembly are indicated by the coefficients of variation: 0.33 and 1.07 respectively.

The next step in the analysis was to attempt to discern any stratification in the data attributable to type of material or type construction. First, if we look at the outliers, assemblies 4006, 5160, 3920, 4130, and 4170, we see types of material and construction as shown in Table 11. This does not vary from that represented by the remaining assemblies. No discernible stratification presents itself.

Table 11. Dispersion of Data by Material and Construction Type.

Assembly No.	Type of Construction	Type of Material
4006	Machined	Aluminum
4160	Rivet and Bolt	Alum ~ T_i
3920	Weld & Machine	Titanium
4130	Machined	Alum ~ T_i
4170	Bonded	10 N_i ~ T_i ~ Al

3.1.4 COMPLEXITY FACTORS. The assembly level as represented in Table 4 is essentially the level at which the basic method was structured for the estimation of primary structure. These assemblies, consisting of ribs, bulkheads, covers, fittings, and plates, were expected to serve as the basis for extending estimating factors for detail fabrication and subassembly to cover the advanced materials and construction methods represented.

The estimating concept and the concept for developing baseline coefficients and complexity factors were reviewed earlier in this section. In that discussion it was pointed out that complexity values were derived from industrial engineering analyses and were used to normalized historical data by material and type of construction. A baseline estimating coefficient was defined as the value of a dependent variable, hours per pound, with the independent variable, weight, at a value of one pound, and with the functional relationship being determined by a log-linear expression having a predetermined slope and passing through a selected data point representing a reference type of construction and material. This same reference was then used for normalizing complexity factor values. Complexity factor values determined by industrial engineering analysis would, ideally, account for the dispersion of data about the estimating line. The extent to which they do is partially a measure of the validity of the factor but not completely because of various other effects that can enter the picture.

In this study, however, complexity is determined by determining the ratio, when normalized by weight, of a given data point in the advanced structures data base to the previously established baseline coefficient. This means that actual data is being used to establish complexity factors rather than comparisons achieved through the previously used industrial engineering method. The key factor in determining these ratios is that they be properly referenced to the types of material and construction involved. This again involves the problem of categorization.

The development of baseline estimating coefficients is not markedly affected by the addition of the advanced structure data points. The original development of these coefficients can be explained by reference to Figure 29, which is a hypothetical construct. Assume a set of data points, as shown, with four of them, those labeled R, representing the same type of material and construction and with four other types represented by points A, B, C and D. Original points are represented by solid circles while the dotted circles are a hypothetical representation of points normalized by division by complexity factors for the corresponding types of construction and material. If the complexity factors were a complete and accurate measure of cost differences and if no anomalies existed, normalization by these factors would result in data points that fell on a straight line for all types of material and construction. The described line could then be used with high confidence as an estimating baseline to develop a baseline estimating coefficient. In fact, however, considerable dispersion still remains after the normalization. The selection of a baseline coefficient therefore proceeds as follows.

First, this coefficient should represent the same type of material and construction as used in the normalization of complexity factors. Typically, this will be a type having a meaningful number of data points, such as R in Figure 29. When this is the case, the reference, or estimating line, is drawn with the predetermined slope in a freehand manner. In the case where the baseline is represented by only a single point, the estimating line will normally be drawn through that point. The baseline estimating coefficient is, in any case, the hours per pound value at a weight of one pound. It should also be noted that, in addition to the scaling of hours per pound by weight, the baseline hours per pound scale by quantity, since the value determined above is a first unit value.

The final step is to use the wing carry-through box data to develop complexity factors for the types of material and construction represented by the data. The pertinent data were plotted on the respective charts of the Estimating Handbook. These data are obatined from Table 5. At the detailed part level, the breakdown between detailed fabrication and subassembly hours is identified. At the subassembly level, however, only detailed fabrication hours are segregated. This is because part of the subassembly task is included in the figure for final assembly of the wing carry-through structure.

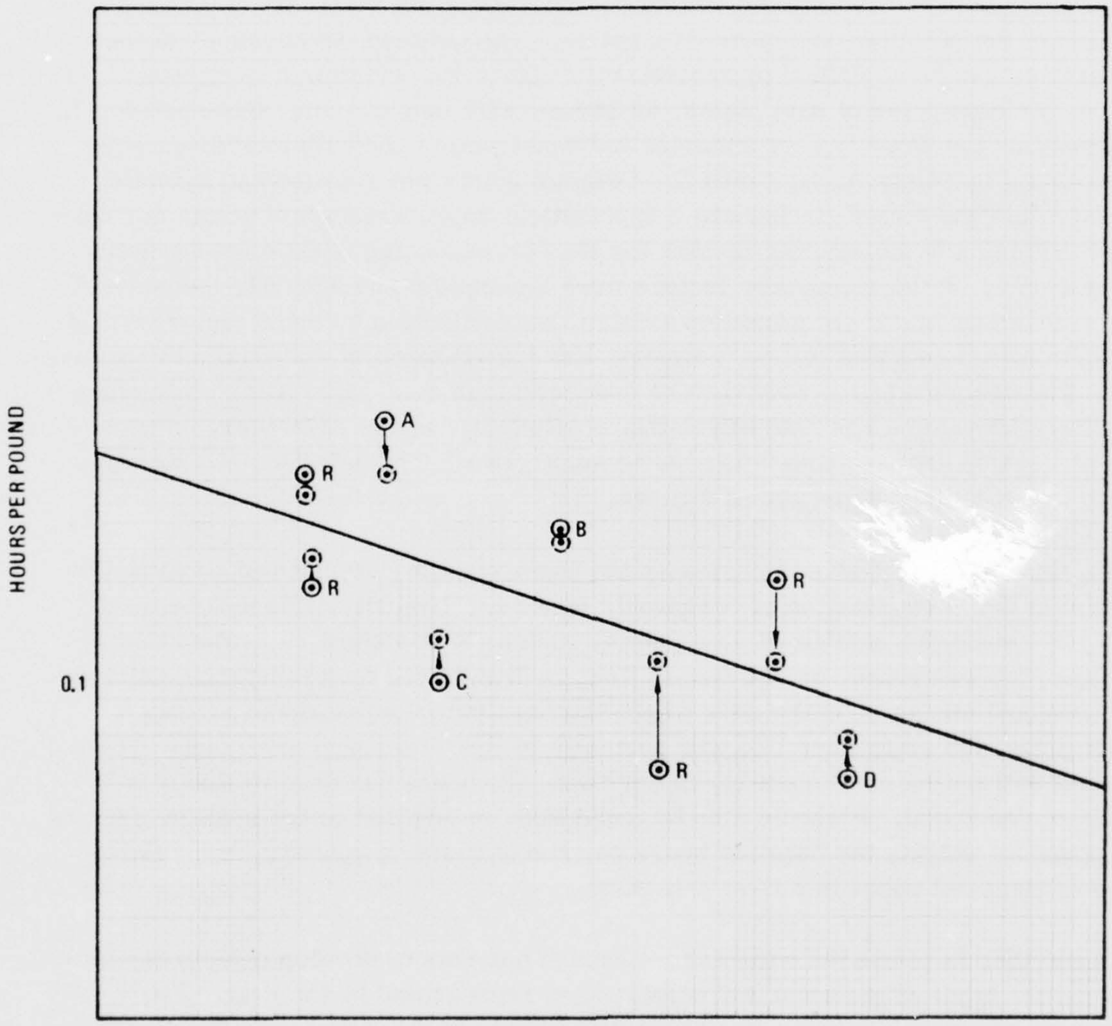

Figure 29. The Development of Baseline Estimating Coefficients.

The plotting of these data involved a number of considerations and judgments:

a. Plotting the lower pivot lug, Part No. 4175-7, as a spar gives the results shown in Figure 30. (The weight of the pivot lug indicates treating it as a spar rather than a rib.) The data point is far below the previously developed reference estimating line as indicated in Figure 30. Calculation of a complexity factor gives a value of 0.15, which indicates a substantial cost reduction due to the new technology. The other data points in Figure 30 represent ship sets of spars for various aerodynamic surfaces. This means that, for the weight, more different designs are represented. This is most likely an added cost factor.

b. Plotting the lower plate and lug assembly, Part No. 4170-1, on Figure 30 gives the results shown. A complexity factor of 0.333 is calculated.

c. Plotting the remainder of the parts making up the lower plate and lug assembly was not accomplished because of their smaller size.

d. The lower fairing assembly, Part No. 4160, is plotted on Figure 31, together with the reference estimating line, with the results shown. The complexity factor in this case is 0.99.

e. The upper cover assembly, Part 4010, is plotted as a fairing and as a cover in Figures 31 and 32, respectively. As a fairing the complexity factor is 0.76. Figure 32 shows the results of covers and a complexity factor of 2.6. The upper cover assembly comprises pivot lugs, beams, stiffeners, skin, skin panels, cores, edge members, and fittings, which makes it more involved than the typical cover assembly. Other plots were made in Figure 32 of skin panels, Part No. 4150-1 and Part No. 4151-1/2.

f. Bulkheads can appear in either the wing or fuselage so Part Nos. 4080-1 and 4060- are compared to both ribs and frames, Figure 33 and 34 respectively. Considered as a rib, from Figure 33, the complexity factors are 0.72 for the forward bulkhead and 0.48 for the aft bulkhead. Considered as frames, the complexity factors are 0.38 and 0.25, respectively. Review of Figure 34 lead to a change in the baseline estimating coefficient from 100 to 81 hours per pound.

g. The centerline rib, Part No. 4110, the X_F 39 rib, Part No. 4120, the closure rib, Part No. 4030, and the X_F 84 rib, Part No. 4130, are plotted on Figure 33, with complexity factors of 0.47, 0.53, 0.70 and 0.32, respectively.

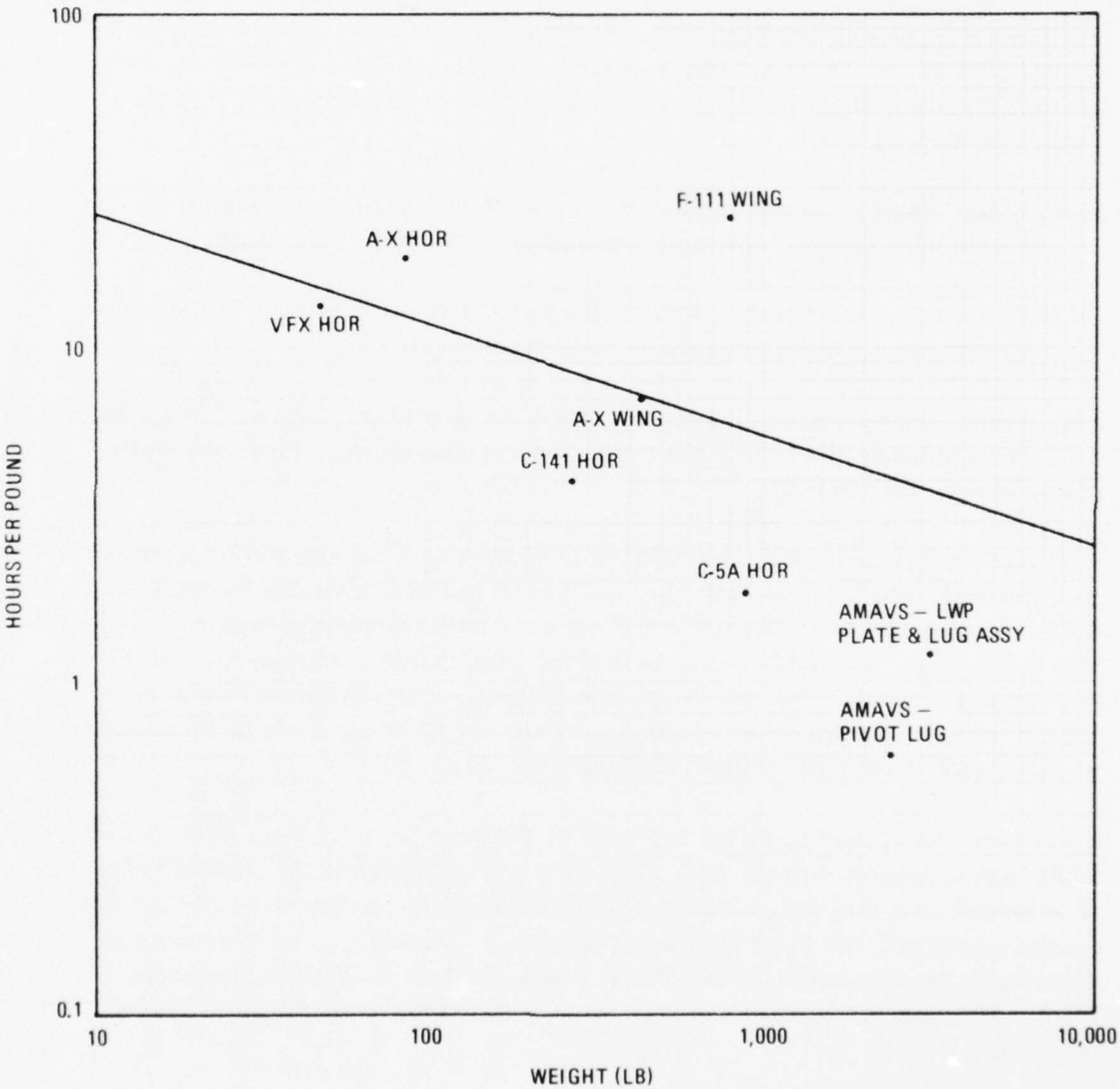

Figure 30. Spar Detail Fabrication Hours Per Pound Against Weight. (Figure F-2 of the Estimating Handbook with the ordinate scale shifted.)

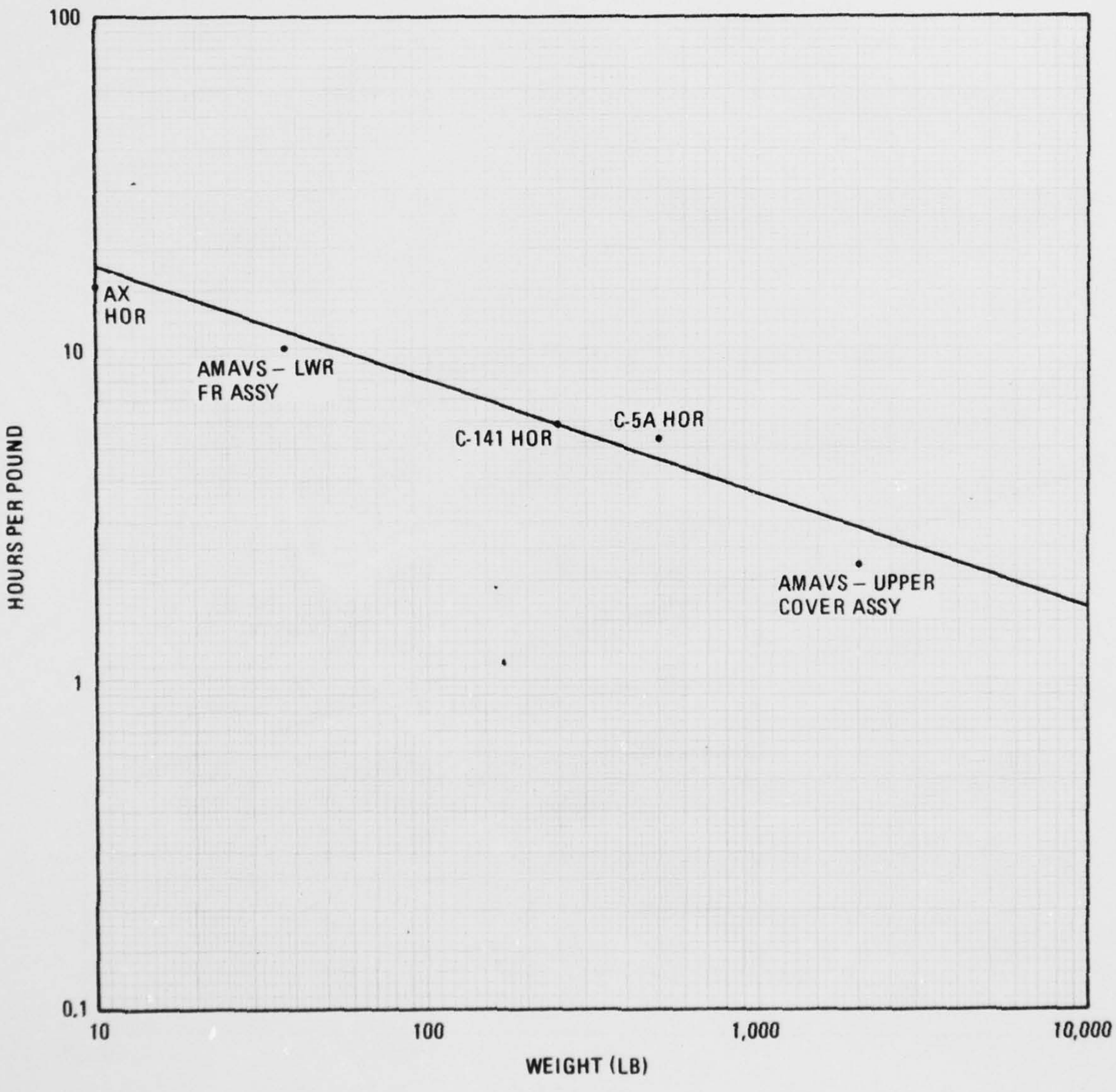

Figure 31. Fairing Detail Fabrication Hours Per Pound Against Weight. (Figure F-18 of the Estimating Handbook with ordinate scale shifted.)

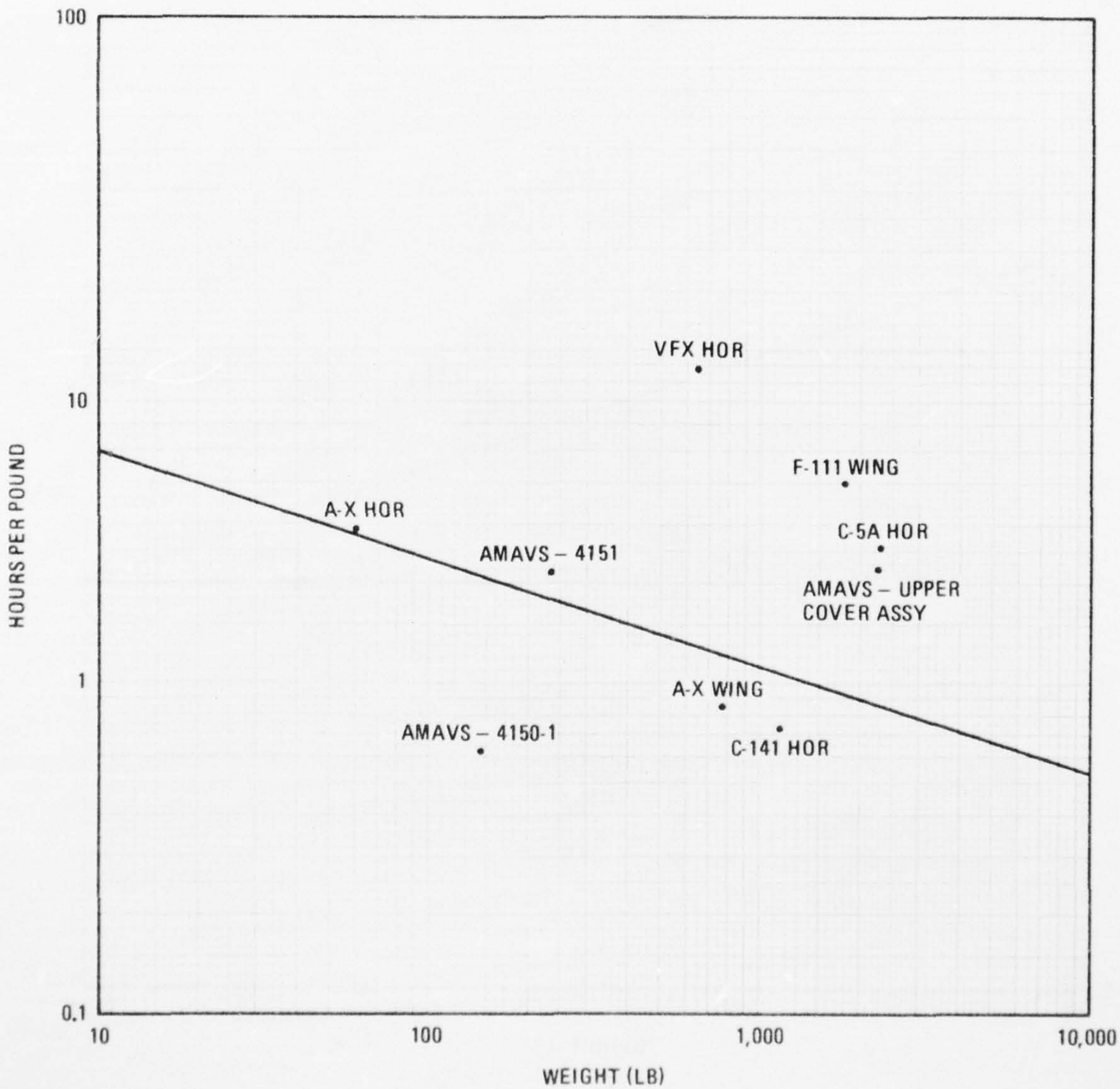

Figure 32. Cover (Aero Surfaces) Detail Fabrication Hours Per Pound Against Weight. (Figure F-3 of the Estimating Handbook)

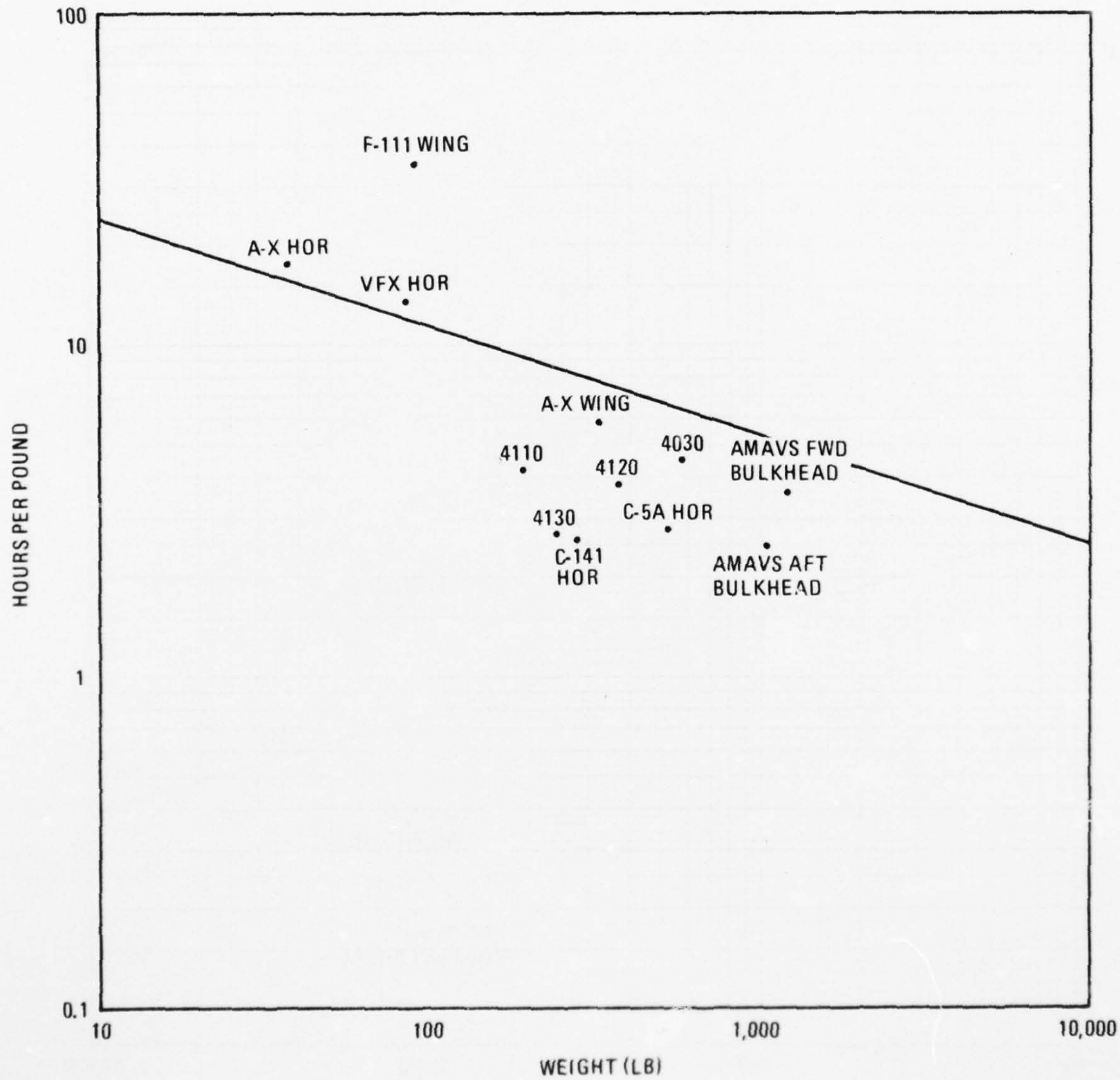

Figure 33. Rib Detail Fabrication Hours Per Pound Against Weight. (Figure F-1 of the Estimating Handbook with both scales shifted.)

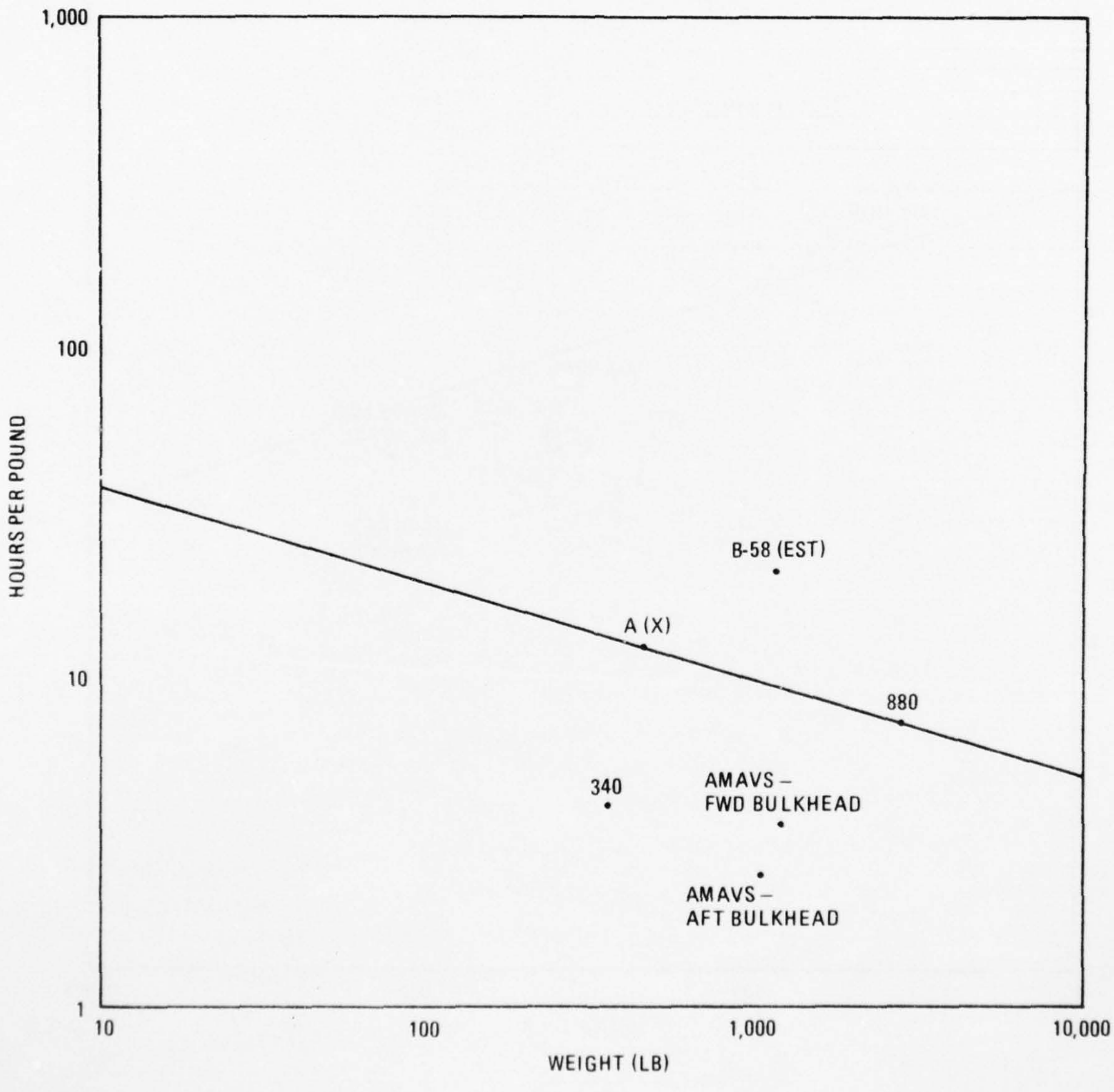

Figure 34. Frame Detail Fabrication Hours Per Pound Against Weight. (Figure F-4 of the Estimating Handbook.)

h. Separate factors were developed for aerodynamic surface and fuselage covers. Plotting the cover and skin panel data from Figure 32 against fuselage data gives the results shown in Figure 35. The resulting complexity factors are upper cost assembly, 0.94, part No. 4151, skin panel, 0.42 and part No. 4150, skin panel, 0.103.

i. Part No. 4118-7/8 is a longeron. The data point is plotted in Figure 36 with a resulting complexity factor of 0.17.

j. Part No. 4006, pivot lug, and part No. 3901, the wing sweep actuator support fitting are plotted in Figure 37 resulting in complexity factors of 0.31 and 1.44 respectively.

k. Four trunnions or fittings from the AMAVS wing carry-through structure are plotted. Detailed fabrication hours are shown in Figure 38. A reference estimating line was not shown in the Estimating Handbook. The line shown on Figure 38 represents an average, first unit, one pound value of 36 hours per pound for machined titanium. Subassembly hours are plotted in Figure 39 with a first unit, one pound value of 16 hours (average value).

l. Total detail fabrication hours for the wing carry-through section are plotted in Figure 40 based on data from Table 8. The complexity factor resulting at this level is 0.83. For subassembly hours, the results are shown in Figure 41. This complexity factor is 0.89.

The resulting complexity factors are summarized in Table 12. These factors indicate complexity vis-a-vis the corresponding estimating reference as determined from the data shown in the figures referenced in Table 12. The materials and types of construction represented by these data were discussed in Reference 1. These figures also provide a means of relating the AMAVS results to previously determined complexity factors.

The relationship and comparison of AMAVS data to previously developed complexity factors shows one significant point: AMAVS costs generally appear to be less than the cost of other representative structural elements. This gives rise to the questions: To what extent is this indicative of the new design and repeatable; to what extent is it due to the fact that the item is experimental and one of a kind; and to what extent is it due to the item being pure structure, uncomplicated by subsystem installations? Since there has been no activity to develop quantitative measures of these effects, these questions will be answered qualitatively. Several production factors lead to the conclusion that the resulting cost savings are indicative of the new design and repeatable:

a. The basic design took producibility into account. Tolerances, cutter radii, slope angles and other factors were given careful consideration.

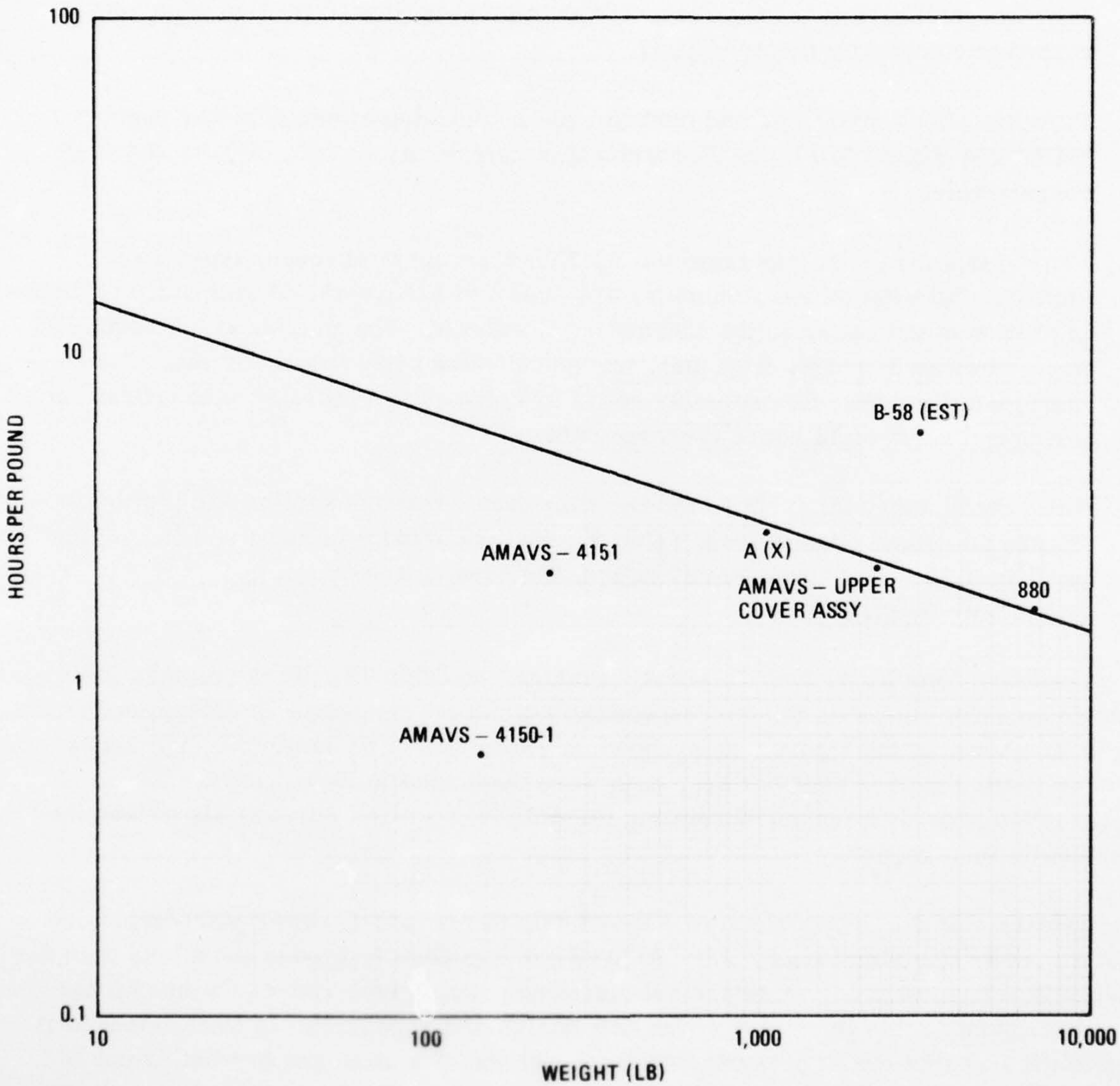

Figure 35. Cover (Fuselage) Detail Fabrication Hours Per Pound Against Weight. (Figure F-6 of the Estimating Handbook with the ordinate scale shifted.)

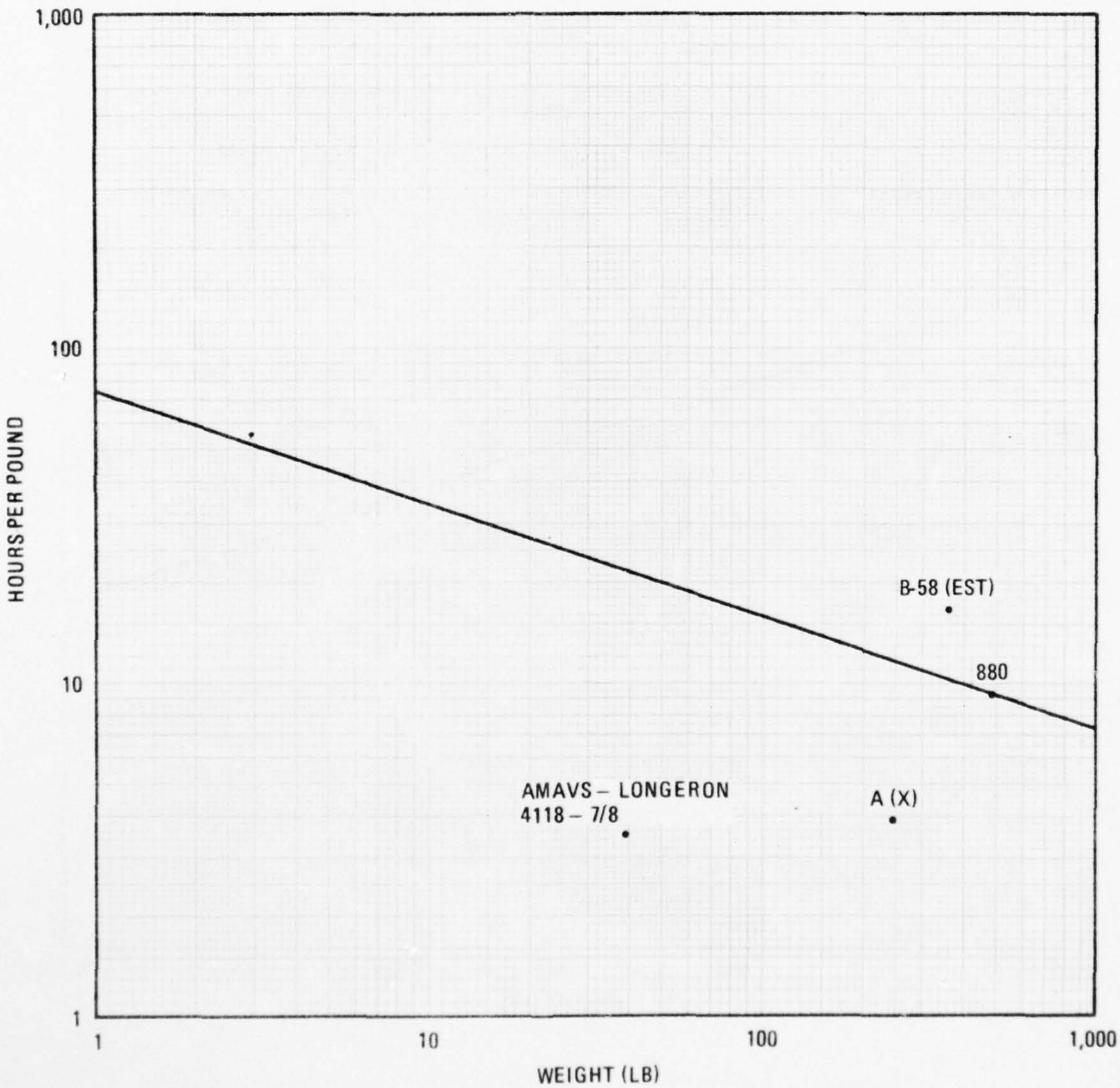

Figure 36. Longeron Detail Fabrication Hours Per Pound Against Weight. (Figure F-5 of the Estimating Handbook.)

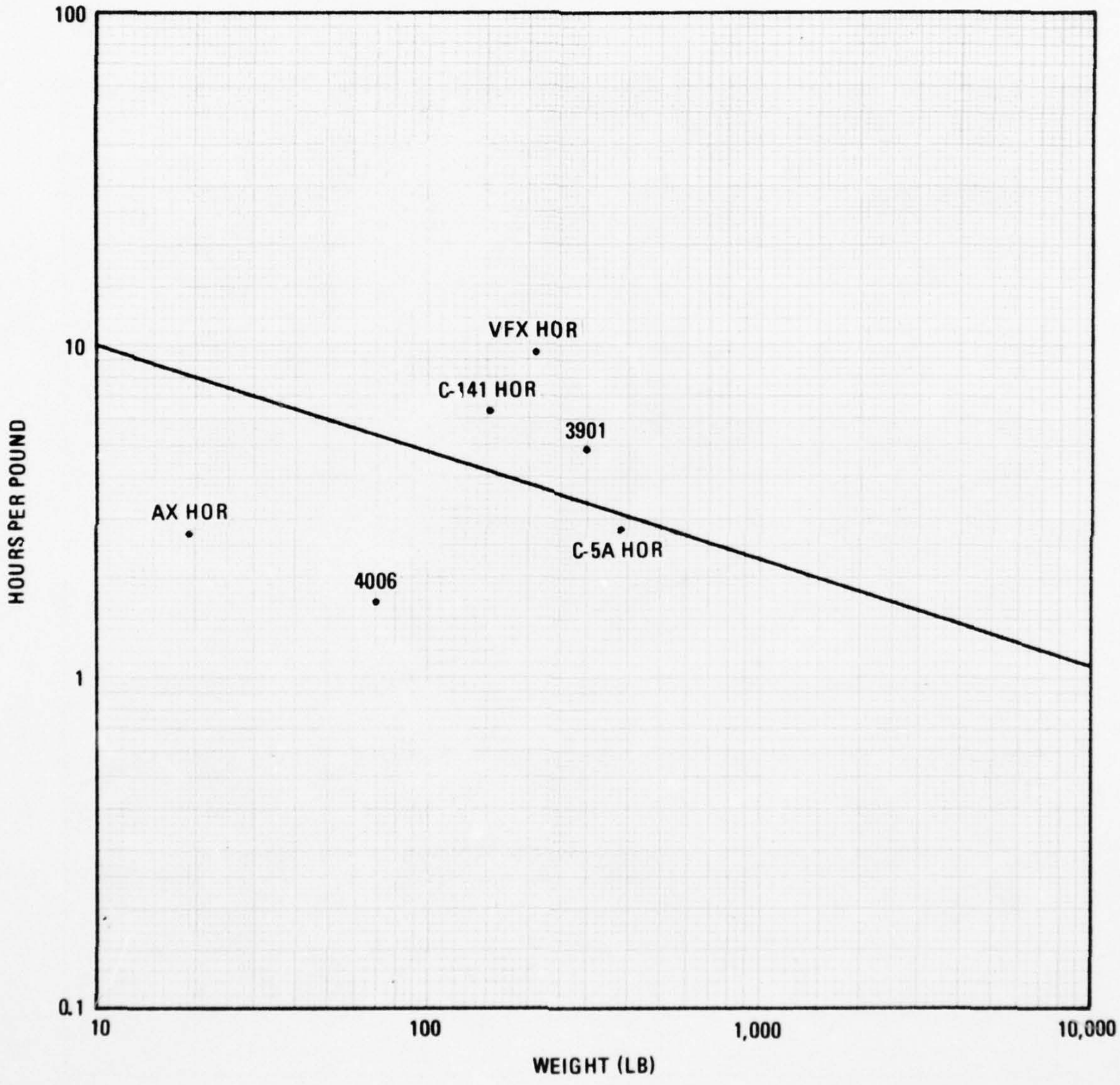

Figure 37. Pivots and Folds Detail Fabrication Hours Per Pound Against Weight. (Figure F-28 of the Estimating Handbook with the ordinate scale shifted.)

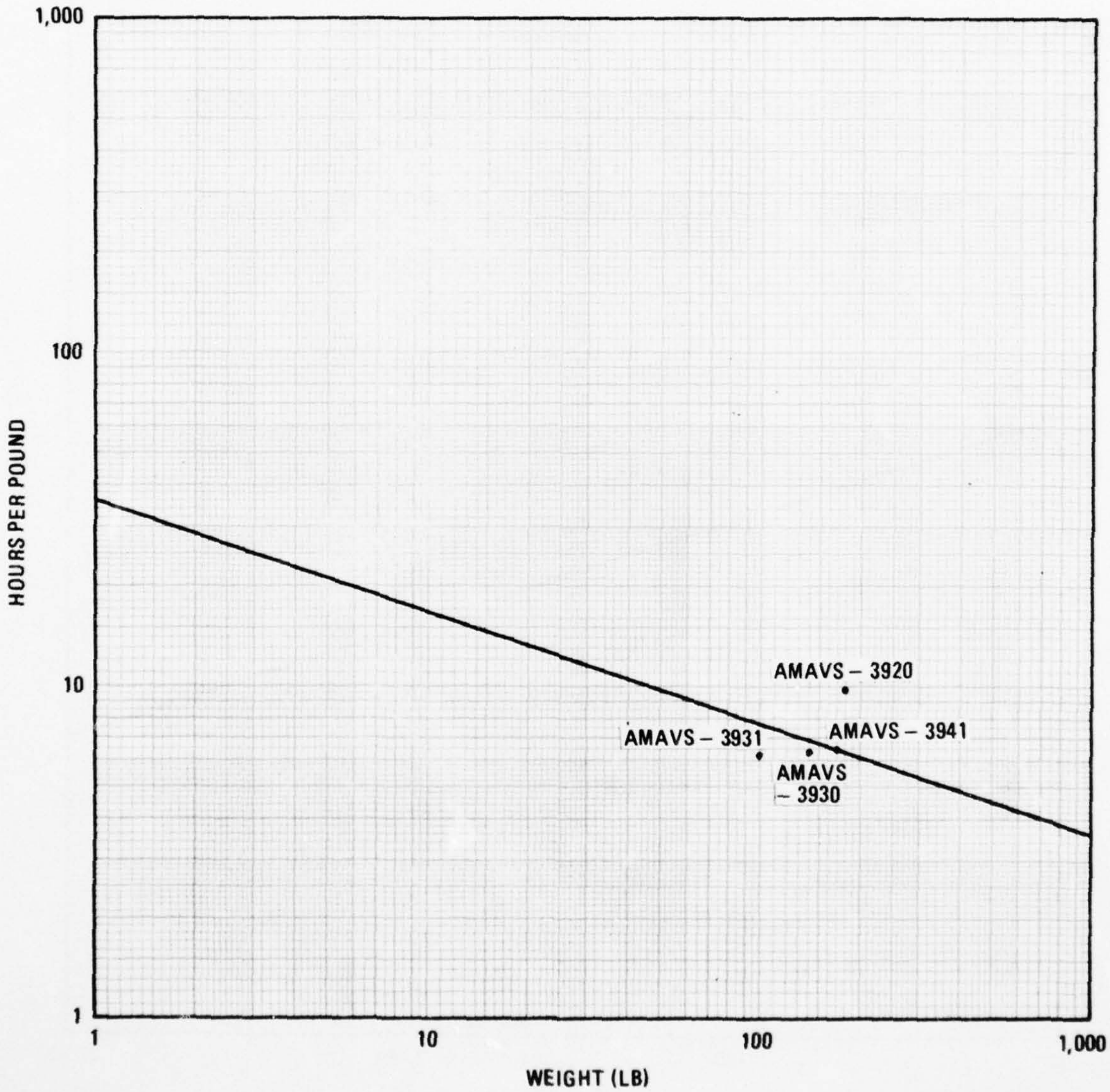

Figure 38. Axles, Trunnions and Fittings Detail Fabrication Hours Per Pound Against Weight. (Figure F-56 of the Estimating Handbook.)

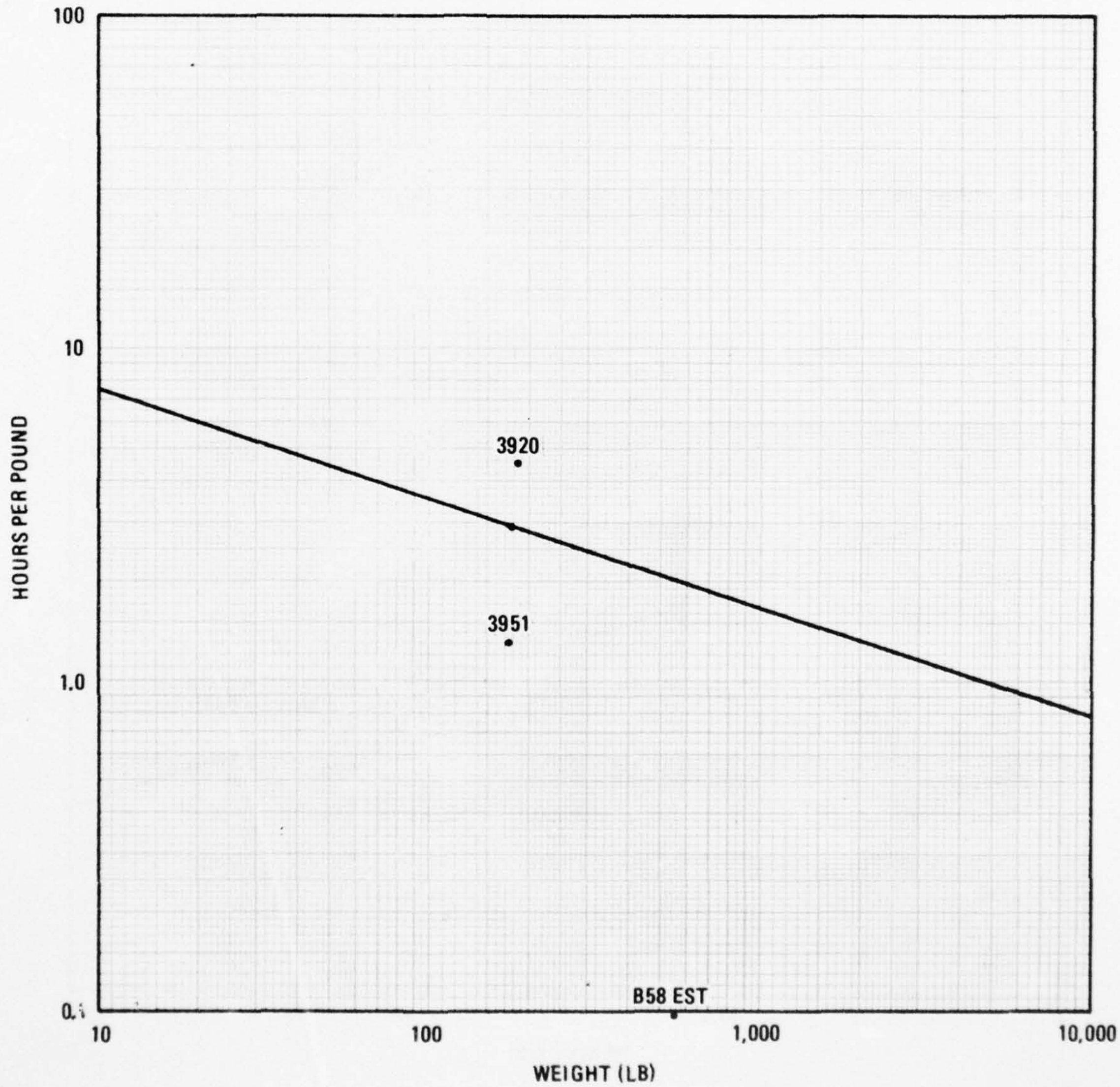

Figure 39. Axles, Trunnion and Fittings Subassembly Hours Per Pound Against Weight. (Figure F-99 of the Extimating Handbook.)

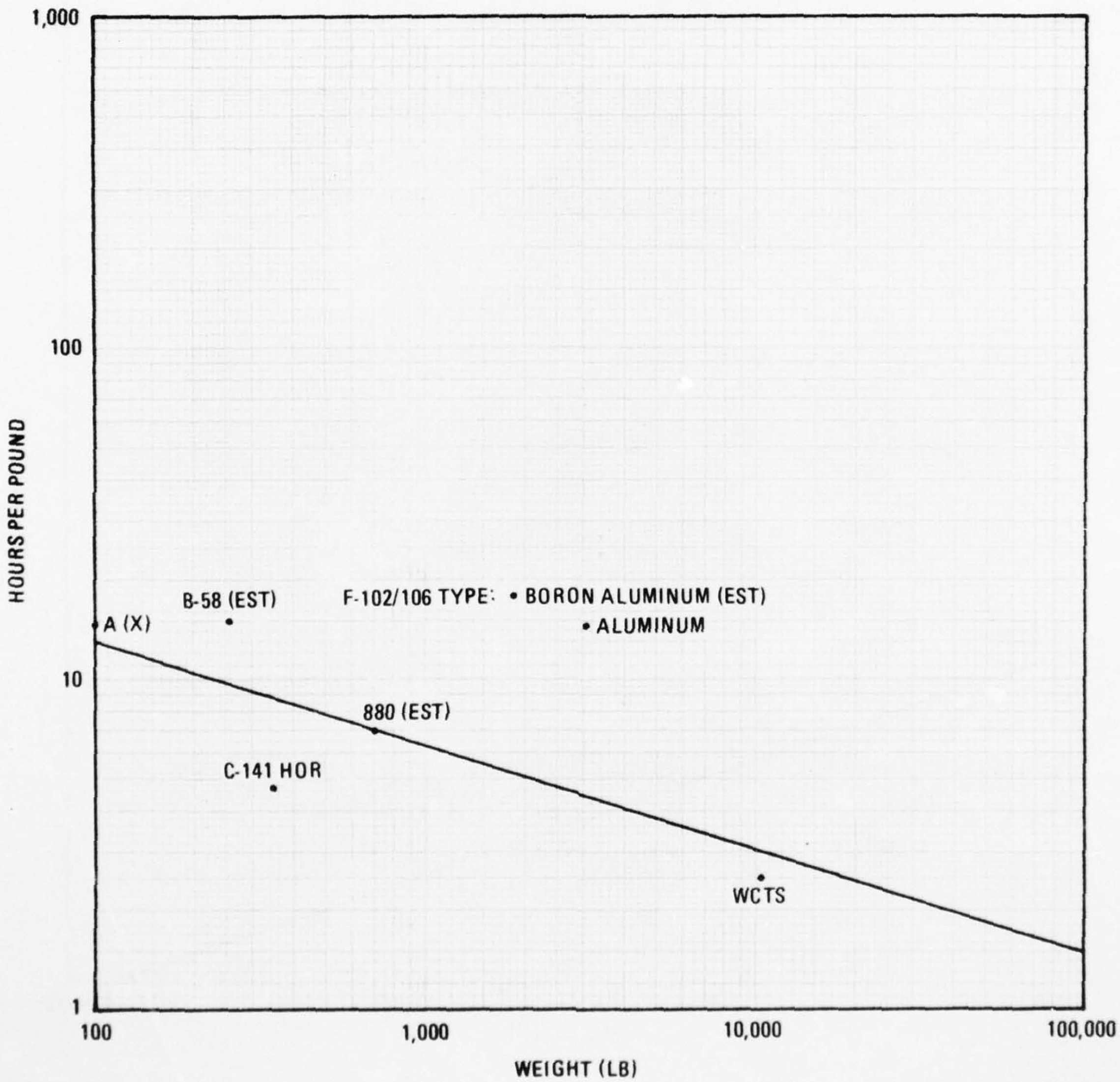

Figure 40. Wing Carry-through Box Detail Fabrication Hours Per Pound Against Weight. (Figure F-36 of the Estimating Handbook.)

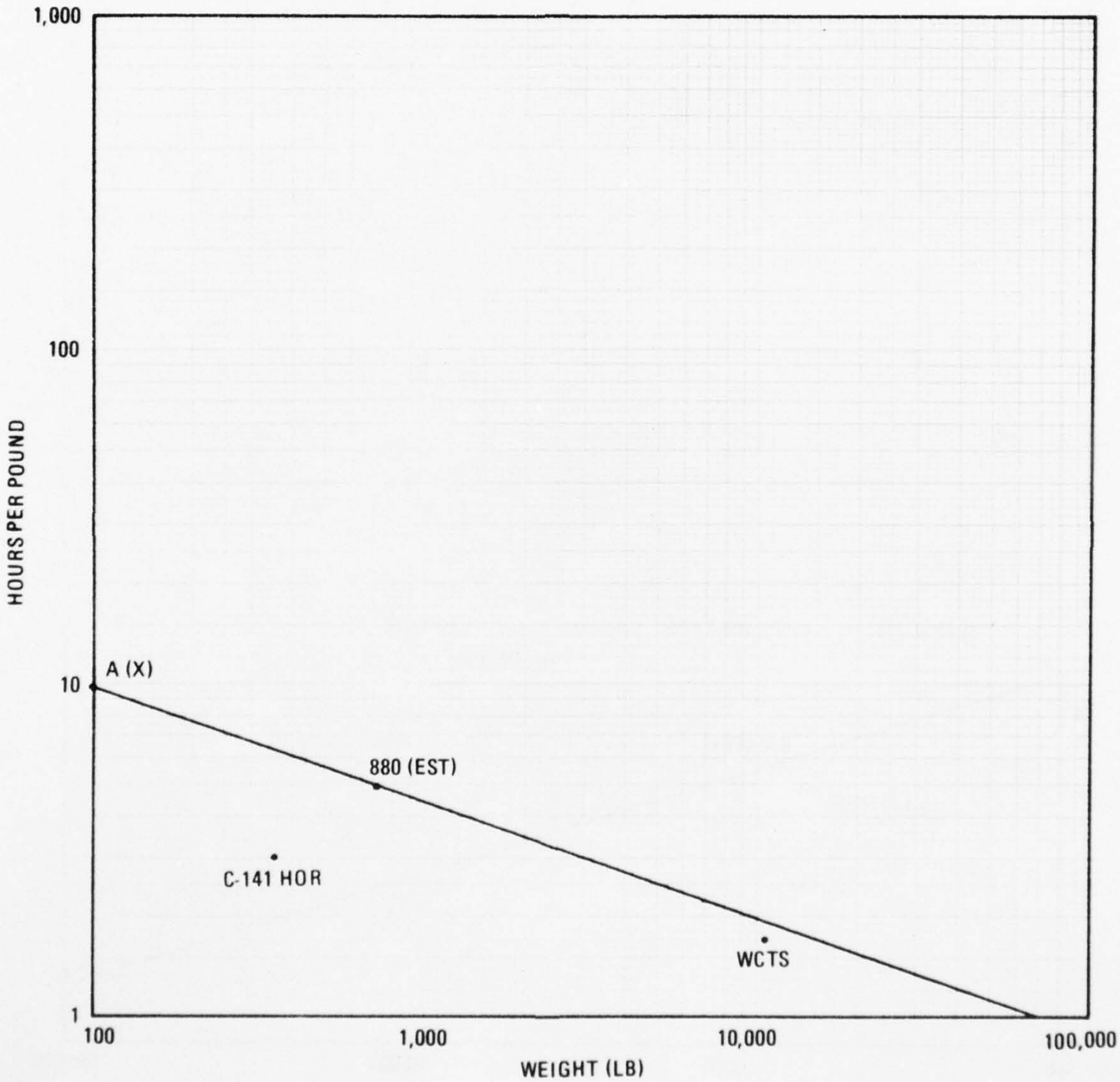

Figure 41. Wing Carry-through Box Subassembly Hours Per Pound Against Weight. (Figure F-79 of the Estimating Handbook.)

Table 12. Complexity Comparison for AMAVS WCTS to Conventional.

Structural Element	Reference hrs/lb @ Complexity = 1	AMAVS WCTS — Component and Complexity Factor			Backup Data	Estimating Handbook Table Reference
Rib - Detail Fabrication	51.3	Forward Bulkhead 0.72	Aft Bulkhead 0.48	Centerline Rib/0.47 X_F 39 Rib/0.53 Closure Rib/0.7 X_F 84 Rib/0.32	Fig. 33	9
Fuselage Frame - Detail Fabrication	81	Forward Bulkhead 0.38	Aft Bulkhead 0.25	∽	Fig. 34	10
Spar - Detail Fabrication (Aero Surfaces)	52	LWP Plate and Lug Assy. 0.333	Pivot Lug 0.15	∽	Fig. 30	11
Fuselage Longeron - Detail Fabrication	65	Longeron Part 4118 0.17	∽	∽	Fig. 36	12
Covers - Detail Fabrication (Aero Surfaces)	85.5	Upper Cover Assy 2.6	Skin Panel Part 4150-1 0.35	Skin Panel Part 4151 1.19	Fig. 32	13
Covers - Detail Fabrication (Fuselage)	29.9	Upper Cover Assy. 0.94	Skin Panel Part 4150-1 0.103	Skin Panel Part 4151 0.42	Fig. 35	14
Fairing - Detail Fabrication	36	Lower Fairing Assy 0.99	Upper Cover Assy 0.77	∽	Fig. 31	

Table 12. Complexity Comparison for AMAVS WCTS to Conventional. (Continued)

Structural Element	Reference hrs/lb @ Complexity = 1	AMAVS WCTS – Component and Complexity Factor			Backup Data	Estimating Handbook Table Reference
Pivots and Folds - Detail Fabrication	21.4	Wing Sweep Activated Spt. Fitting 1.41	Pivot Lug 0.31		Fig. 37	
Axles, Trunnions and Fittings - Detail Fabrication	36*	X_F 955 Trunnion (3931) 0.79	X_F 70 Trunnion (3930) 0.91	MLG Side Brace (3920): 1.52 MLG Drag Ftg (3941): 1.0	Fig. 38	
Axles, Trunnions and Fittings - Subassembly	16	MLG Side Brace (3920) 1.58	MLG Drag Ftg (3941) 0.45		Fig. 39	

*Value for Titanium

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WEAPON SYSTEM COSTING METHODOLOGY IMPROVED STRUCTURAL COST ANAL--ETC(U)

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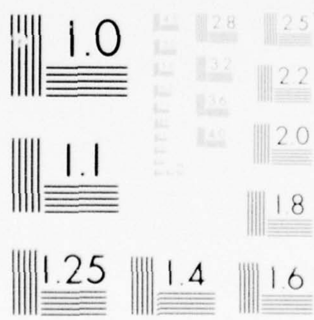

MICROCOPY RESOLUTION TEST CHART
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b. Tools were built with Numerical-Control procedures.

c. Holes were design coordinated. The engineering graphics group established coordinates for each hole. Holes were numbered, a tabulation was printed, and the information was given to the machine shop and the tooling shop. Errors were greatly reduced due to the more precise control, better coordination and reduction in the requirement for multiple measurements. Set-up time was minimized and alignment errors during assembly were greatly reduced.

It is not clear, in this case, in which direction, greater or less cost, the experimental and one of a kind factors operated. It is thought, however, that the effect is negligible.

There is obviously a difference in the cost of structure depending upon whether it is defined with or without the structural elements associated with air vehicle subsystems. The comparisons made to AMAVS in the various data presentations is valid, however, since data points for conventional structure were selected or adjusted so as to eliminate this effect.

3.1.5 TOOLING FACTORS

Cost-on-Cost Relationship for Tool Planning

In assessing the data in Table 4, a consistent relationship was noted between Tool Planning hours and Fabrication hours. The ratios between these values were calculated and are summarized in Table 13 together with pertinent statistical measures. The standard deviation has a very low value and the coefficient of variation is a very acceptable 17%.

Basic Tool Manufacturing Hours

In the estimating method described in Reference 1, tool manufacturing is estimated as a relationship to structural weight by means of the following equation:

$$(1) \qquad BTMH_i = TMF_i\,(WAMPR_i)^{ET}$$

where

$BTMH_i$ = Basic Tool Manufacturing Hours by major component

(1) Equation (28), Reference (1) Vol. II, Part 1.

Table 13. AMAVS WCTS - Tool Planning/Fabrication Hours Relationships

Part No.	NAME	Tool Plng. Hrs/ Fab. Hrs.	$(X_i - \overline{X})$
4001	WCTS Assembly	.273	-.005
3920	MLG Side Brace	.265	-.013
3930	XF 70 Trunnion	.262	-.016
3931	XF 95.5 Trunnion	.257	-.021
3941	MLG Drag Fitting	.194	-.084
3950	Wing Sweep Fitting	.335	.057
4006	Pivot Lug Rib	.28	.002
4010	Upper Cover	.243	-.035
4030	Outboard Rib	.26	-.018
4060	Bulkhead YF 992	.28	.002
4080	Bulkhead YF 932	.273	-.005
4110	Centerline Rib	.285	.007
4120	XF 39 Rib	.274	-.004
4130	XF 84 Rib	.267	-.011
4160	Lower Fairing	.28	.002
4170	Lower Plate	.43	.152
		X = .278 S = .0474 V = 17%	$\sum (X_i - \overline{X})^2$ = .036

S = Standard deviation of the sample.

V = Coefficient of variation (S/X).

TMF_i = Empirical estimating coefficient by component

ET = Scaling exponent, tool manufacturing hours to weight.

This equation is used to estimate at the major component level, i.e., wing, fuselage, horizontal stabilizer, etc. Other elements of tooling costs are then estimated from the tool manufacturing estimate. Applying this equation to the wing carry-through structure at an aggregate level gives inconclusive results. This is because AMAVS actuals are based on experimental tooling, the structure itself is in the nature of a structural box rather than a finished aerodynamic component, and in the component level method, all tool manufacturing costs are accounted for.

The following analysis then explores the relationship between tool manufacturing hours and structural weight for the wing carry-through structure at the next level of indenture. Table 14 gives detailed calculations. The values for X are previously used weights. Values for Y are from Table 6. Then,

$$a_o = \log a = \frac{(.382)(81.998) - (30.622)(.844)}{12(81.998) - (30.622)^2}$$

$$= \frac{31.32 - 25.84}{983.976 - 937.71} = \frac{5.48}{46.27} = .1184$$

and

$$a = 1.313$$

$$a_1 = b = \frac{12(.844) - (30.622)(.382)}{12(81.998) - (30.622)^2} = \frac{10.128 - 11.698}{46.27} = \frac{-1.57}{46.27}$$

$$= -.034$$

Then,

$$Y = 1.313X^{-.034}$$

The data points and the line for this equation are plotted on Figure 42.

The standard error of estimate of Y on X is given by

$$S^2_{Y \cdot X} = \frac{(.494) - .1184(.382) - (-.034)(.844)}{12}$$

$$= \frac{.494 - .045 + .0287}{12} = .0398$$

Table 14. Calculation of Statistics for Basic Tool Manufacturing Hours

Part No.	X = log X	Y = log Y	X^2	Y^2	XY
3920	2.276	.342	5.180	.117	.778
3920	2.230	-.398	4.973	.158	-.887
3941	2.230	.114	4.973	.013	.254
4006	1.845	-.155	3.404	.024	-.286
4010	3.346	-.155	11.196	.024	-.519
4030	2.693	-.046	7.252	.002	-.124
4060	3.004	.146	9.024	.021	.439
4080	3.079	-.046	9.480	.002	-.142
4110	2.276	.279	5.180	.078	.635
4120	2.577	.222	6.641	.049	.572
4160	1.568	.079	2.459	.006	.124
4170	3.498	0.	12.236	0	0
	$\sum X =$ 30.622	$\sum Y =$ .382	$\sum X^2 =$ 81.998	$\sum Y^2 =$ .494	$\sum XY =$ .844

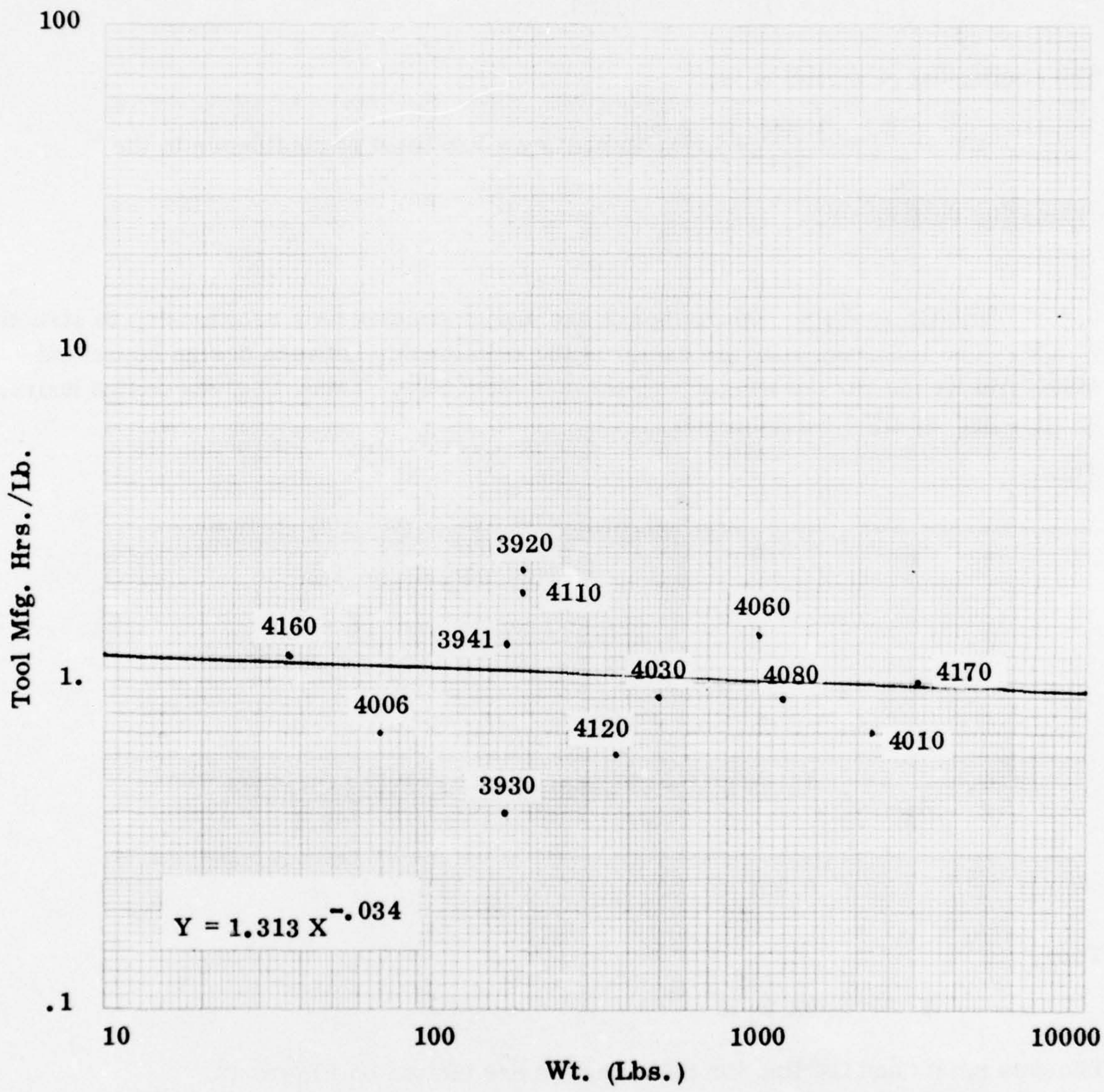


Figure 42. Wing Carry-through Box Assemblies - Tool Mfg. Hours Against Weight.

$$S_{Y \cdot X} = .1995, \text{ which is for } Y = \log Y.$$

Then for Y = Y,

$$S_{Y \cdot X} = 10^{.1995} = 1.583.$$

The coefficient of variation is,

$$CV = \frac{SE}{\bar{Y}} = \frac{1.583}{1.1} = 1.44,$$ indicating a low level of confidence in the estimating relationship.

3.1.6 DESIGN HOURS. Design hours are also estimated as a relationship to structural weight. The following analysis explores the relationship between design hours and structural weight for the wing carry-through structure. Table 15 gives design hours, weights and detailed calculations.

Then,

$$a_o = \log a = \frac{(1.674)\,(106.046) - (40.368)\,(2.164)}{16\,(106.046) - (40.368)^2}$$

$$= \frac{177.52 - 87.36}{1696.7 - 1629.6} = \frac{90.16}{67.1} = 1.344$$

$$a = 22.08$$

$$a_1 = \frac{16\,(2.164) - (40.368)\,(1.674)}{67.1} = \frac{34.624 - 67.58}{67.1}$$

$$= -.491$$

Then,

$$Y = 22.08\, X^{-.491}$$

The data points and the line for this equation are plotted on Figure 43.

Data are for the so-called "No-Box Box" configuration of the wing carry-through box. Initially, design included both that configuration and the Fail - Safe Integral Lug configuration. Design hours were intermixed necessitating a formula for allocating to an NBB hours only basis. This was accomplished by counting drawings and making an allocation by number of drawings and their size and complexity. The resulting data at the subassembly level is given in Table 16.

Table 15. Calculation of Statistics for Design Hours

Component	Drawing	Weight (Lbs) (X)	Design Hours	Hours/Lb (Y)	X = log X	Y = log Y	X^2	Y^2	XY
Lower Plate	4170	3147	819	.26	3.498	-.585	12.236	.342	-2.046
Upper Cover	4010	2216	1139	.514	3.346	-.289	11.196	.084	-.967
Forward Bulkhead	4080	1200	1377	1.148	3.079	.060	9.480	.004	.185
Aft Bulkhead	4060	1011	1532	1.515	3.004	.180	9.024	.032	.541
Centerline Rib	4110	189	570	3.016	2.276	.479	5.180	.229	1.090
X_F 39 Rib	4120	378	654	1.730	2.577	.238	6.641	.057	.613
X_F 84 Rib	4130	239	374	1.565	2.378	.195	5.655	.038	.464
Closure Rib	4030	493	637	1.292	2.693	.111	7.252	.012	.299
MLG Side Fittings	3920	189	395	2.090	2.276	.320	5.180	.102	.728
MLG Trunnion Fittings	3930	170	81	.476	2.230	-.322	4.973	.104	-.718
MLG Trunnion Fittings	3931	107	54	.505	2.029	-.297	4.117	.088	-.603
MLG Drag Fittings	3941	170	305	1.794	2.230	.254	4.973	.065	.566
Wing Sweep Fittings	3950	365	242	.663	2.562	-.178	6.564	.032	-.456
Lug Rib Fittings	4006	70	118	1.686	1.845	.227	3.404	.052	.419
Lower Fairing Support	4160	37	655	17.703	1.568	1.248	2.459	1.558	1.957
Final Assy	4001	598	646	1.080	2.777	.033	7.712	.001	.092
			9598		$\sum X = 40.368$	$\sum Y = 1.674$	$\sum X^2 = 106.046$	$\sum Y^2 = 2.800$	$\sum XY = 2.164$

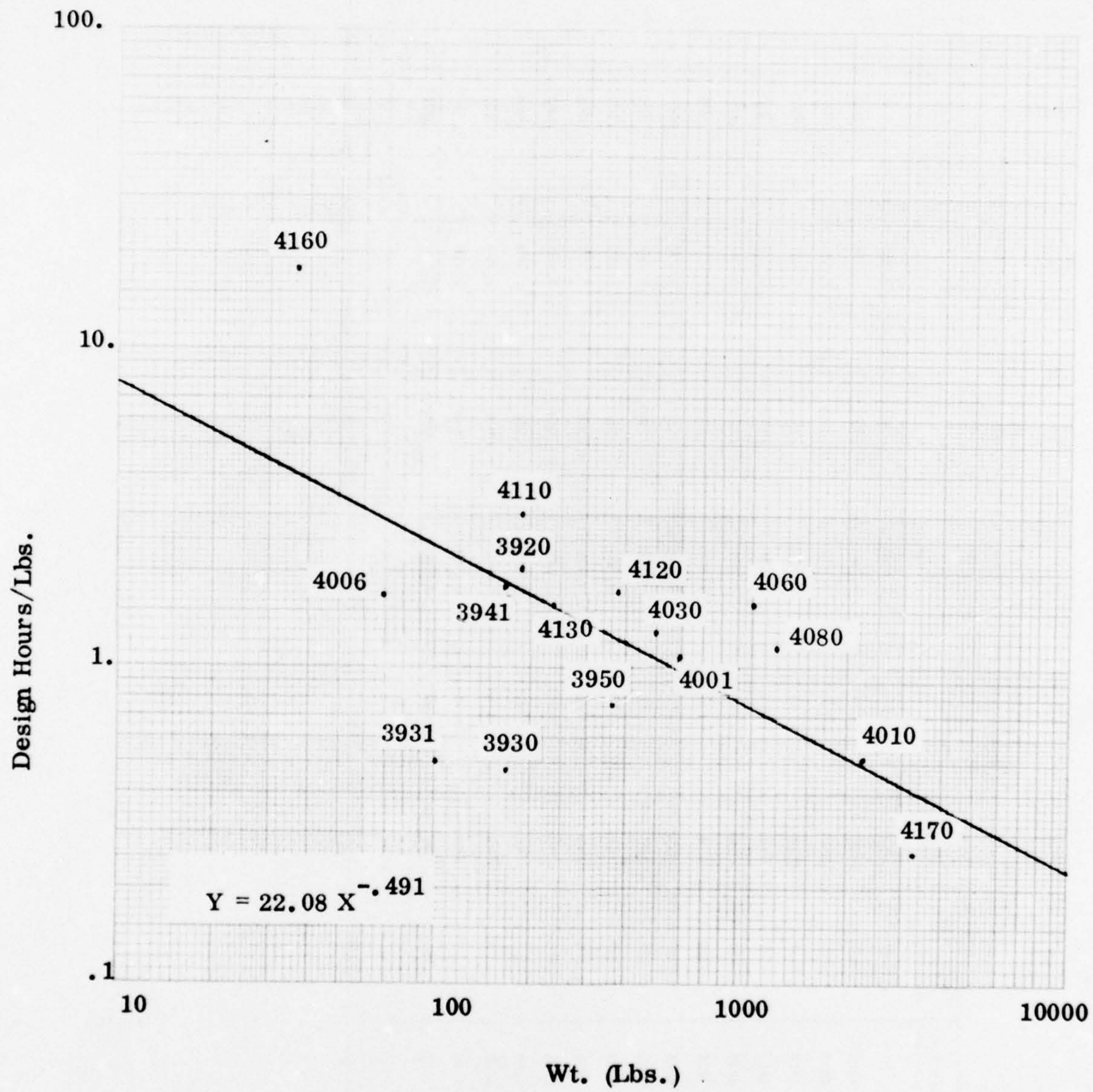


Figure 43. Wing Carry-through Box Assemblies - Design Hours Against Weight.

Table 16. AMAVS Summary.

Component	Dwg.	Detail Design Hr.	Weight (Lbs.)	Cost
Lower Plate	4170	819	3,147	$ 318,774
Upper Cover	4010	1139	2,216	238,088
Fwd BHD	4080	1377	1,200	213,452
Aft BHD	4060	1532	1,011	208,067
℄ Rib	4110	570	189	39,245
X_F Rib	4120	654	378	51,773
X_F Rib	4130	374	239	30,768
Closure Rib	4030	637	493	92,916
Fittings				
MLG Side	3920	395	189	69,255
MLG Trunnion	3930	81	170	37,295
MLG Trunnion	3931	54	107	22,519
MLG Drag	3941	305	170	56,258
Wing Sweep	3950	242	365	72,921
Lug Rib	4006	118	70	4,485
Lwr. Fairing Support	4160	655	37	12,179
Final Assy	4001	646	598	381,126
Total GD/FW Design		9598	10,579	$1,849,121

Note: Design Hr. & Wt for components reflect detail part grouping the same as Manufacturing Engineering cost breakdown.

This relationship differs from that shown in Reference 1, p. 119, inasmuch as different levels of detail are being considered.

3.2 RAW MATERIAL COSTS

The current structural material cost estimating method uses an estimating relationship of the same general form for both primary and secondary structure. For primary structure the form is as follows:

$$M_i = W_i^G (RMC_i) (SF_i) + W_i^G (RMC_i) (SF_i) + W_i^G (RMC_i) (SF_i)$$

where

M_i	=	material cost for ribs, frames, spars, longerons and covers of the component estimated
W_i	=	finished weights of the components estimated,
G	=	cost-weight scaling exponent
RMC_i	=	a series of raw material costs per pound for each type of component estimated,
SF_i	=	a series of scrappage factors related to the material and component estimated.

For secondary structure the form is:

$$M_i = WD_i^G (RMC_i) (SF_i)$$

where

M_i	=	material cost for secondary structure components
WD_i	=	finished weights of the secondary structure components being estimated
G	=	cost-weight scaling exponent
RMC_i	=	a series of raw material costs performed for each type of component estimated
SF_i	=	a series of scrappage factors related to the material and component estimated

As can be seen the form for primary structure is expanded to provide additive expressions for up to three different types of material in a given component, paralleling the labor estimating methodology. The forms are the same, otherwise, except for this one additional difference: The terms RMC and SF have different meanings and values in each form, and they are obtained from different input sources.

During the previous study, look-up tables were developed for each of these terms except in the case of the secondary structure scrappage factor, which was given the value of one pending further development of the estimating concept. During this study, these tables have been expanded. The remainder of this section is devoted to describing: the previously developed tables, their usage, and this study and the resulting tables.

3.2.1 PREVIOUSLY DEVELOPED TABLES AND THEIR USAGE

Primary Structure

Raw material cost per pound and scrappage factors are input as shown in Figure 44 (as NAMELIST inputs in the computer program). Input values are obtained, respectively, from Tables 17 and 18. The term G is the same for both primary and secondary structure and was determined to have a value of 0.77.

Secondary Structure

For secondary structure, raw material cost per pound and scrappage factors are input as shown in Figure 45. The input value for the raw material cost factor is obtained from Table 19. As stated previously, the scrappage factor was assigned a value of one pending the results of this study. The expected form of a suitable table had been described in Table 20.

Back-up data and factor development for each of the above situations was given in Reference 1.

3.2.2 EXPANDED MATERIAL ESTIMATING FACTORS

3.2.2.1 Study Approach. The purpose of this task was to expand the existing look-up tables. In the case of raw material costs, a cost per pound matrix relating raw material cost to differing product forms was required. This is needed to differentiate low-cost forms, such as sheet and billet, from more expensive forms, such as forgings and formed extrusions. In the case of the scrappage factor, a distinction is made between material removal and scrappage of parts due to damage or inferior quality of the part. Material removal accounts for the difference between design weight and the planned weight used in cost estimating and is related to type of material and product form.

INPUT ELEMENTS - DETAIL FABRICATION HOURS: AERODYNAMIC SURFACES STRUCTURAL BOX AND FUSELAGE BASIC STRUCTURE							
Input Symbol	INPUT NAME	INPUT VALUE BY STRUCTURAL ELEMENT					
		Wing	Horizontal Stabilizer	Vertical Stabilizer	Fuselage	Nacelle	Landing Gear
RMC1	Raw Material Cost for Rib or Frame of Type A					NOT USED	NOT USED
RMC2	Raw Material Cost for Rib or Frame of Type B						
RMC3	Raw Material Cost for Rib or Frame of Type C						
SF1	Scrappage Factor for Rib or Frame of Type A						
SF2	Scrappage Factor for Rib or Frame of Type B						
SF3	Scrappage Factor for Rib or Frame of Type C						
RMC4	Raw Material Cost for Spar or Longeron of Type A						
RMC5	Raw Material Cost for Spar or Longeron of Type B						
RMC6	Raw Material Cost for Spar or Longeron of Type C						
SF4	Scrappage Factor for Spar or Longeron of Type A						
SF5	Scrappage Factor for Spar or Longeron of Type B						
SF6	Scrappage Factor for Spar or Longeron of Type C						
RMC7	Raw Material Cost for Covers of Type A						
RMC8	Raw Material Cost for Covers of Type B						
RMC9	Raw Material Cost for Covers of Type C						
SF7	Scrappage Factor for Covers of Type A						
SF8	Scrappage Factor for Covers of Type B						
SF9	Scrappage Factor for Covers of Type C						

Figure 44. NAMELIST Inputs for Structural Box and Fuselage Basic Structure Material Worksheet.

WORKSHEET

*Table 17. Primary Structure Raw Material Cost Factor (RMC)

	Aluminum	Steel	Titanium	Aluminum and Steel
Ribs, Frames, Spars, Longerons, and Covers - Production Material	18.0	22.0	28.0	

*Table 31 in Reference 1.

Table 18. Primary Structure Material Scrappage Factor (SF)

Structure Type

	Material Type	Built-Up Web Stiffener	Built-up Truss	Sheet Web	Corru-gated Web	Integral Web Stiffener	Integral Truss
Ribs, Frames	Aluminum	2.0	2.0	2.0	2.0	5.3	5.3
	Titanium	3.5	3.5	3.5	3.5	5.3	5.3
	Steel						
Spars, Longerons	Aluminum	3.0	3.0	3.0	3.0	5.3	5.3
	Titanium	3.0	3.0	3.0	3.0	5.3	5.3
	Steel						
		Built-up Skin Structure	Integral Skin Stringer	Machined Plate	Sheet		
Covers	Aluminum	2.0	5.3	4.5	1.0		
	Titanium	3.5	5.3	4.5	1.0		
	Steel				1.0		

*Table 32 in Reference 1

INDEX	INPUT ELEMENTS — SECONDARY STRUCTURE STRUCTURAL MATERIAL COST		
	SECONDARY STRUCTURE COMPONENTS	INPUT VALUE	
		Raw Material Cost RMC_i	Scrappage Factor SF_i
	<u>WING</u>		
1	Leading Edge		
2	Trailing Edge		
3	Ailerons		
4	Fairings		
5	Tips		
6	Spoilers		
7	Flaps & Flaperons		
8	Attachment Structure		
9	Access & Other Doors		
10	Air Induction		
11	High Lift Ducting		
12	Slats		
13	Hinges, Brackets, Seals		
14	Pivots and Folds		
15	Center Section		
16	Other		
	<u>HORIZONTAL STABILIZER</u>		
1	Leading Edge		
2	Trailing Edge		
4	Fairings		
5	Tips		
8	Attachment Structure		
9	Access & Other Foors		
13	Hinges, Brackets, Seals		
14	Pivots & Folds		
15	Center Section		
16	Elevators		
17	Balance Weights		
	<u>VERTICAL STABILIZER</u>		
1	Leading Edge		
2	Trailing Edge		
4	Fairings		
5	Tips		

Figure 45. NAMELIST Inputs for Secondary Structure Structural Material Cost Worksheet.

INDEX	SECONDARY STRUCTURE COMPONENT	INPUT VALUE	
		Raw Material Cost RMC_i	Scrappage Factor SF_i
	VERTICAL STABILIZER (Cont)		
8	Attachment Structure		
9	Access & Other Doors		
13	Hinges, Brackets, Seals		
17	Rudder		
	FUSELAGE		
1	Cockpit		
2	Nose Landing Gear Door & Box		
3	Wing Reaction (carry-thru) Box		
4	Tail Attachment		
5	Windshield & Canopy		
6	Main Landing Gear Doors & Box		
7	Final Provisions		
8	Engine Provisions		
9	Duct Provisions		
10	Stores Provisions		
11	Speed Brakes		
12	Cabin Flooring & Supports		
13	Windows & Window Frames		
14	Doors & Door Frames		
	NACELLES		
1	Colwings		
2	Pylons		
3	Main Landing Gear Door & Reinforcements		
	LANDING GEAR		
1	Brakes		
2	Brake Controls		
3	Wheels		
4	Tires		
5	Oleos		
6	Axles, Trunnions & Fittings		
7	Drag Braces		

Figure 45. NAMELIST Inputs for Secondary Structure Structural Material Cost Worksheet. (Continued).

Table 19. Secondary Structure Raw Material Cost Factor (RMC)

	Aluminum	Steel	Titanium	Aluminum and Steel
Secondary and Other Structure Basic Material	70.0	94.0	120.0	85.0*

* Use when aluminum secondary structure includes a steel pivot.

Back-up data appears in Appendix H.

Table 20. Secondary Structure Material Scrappage Factor (SF)

(This table is reserved for future development of factors indicated, and will be of the following form.)

Type of Construction	Material			
	Aluminum	Steel	Titanium	Fibreglass
Leading Edge:				
Typical Construction:				
-				
-				
-				
-				
Trailing Edge:				
Typical Construction				
-				
-				
-				
-				
-				
Etc.:				

The expansion of tables necessitated revised formats. These are illustrated in the tables described below.

3.2.2.2 Method Development Review. This study proceeds from the methodological basis developed during the previous study. The development is briefly reviewed below.

Primary Structure

For primary structure the development was as follows. Data was collected and plotted as shown in Figure 46 and then used to develop the terms RMC_i and SF_i (as defined for primary structure) summarized in Tables 17 and 18, respectively. These costs included the following elements that are to be the subject of analysis.

a. Mill costs

b. Scrappage from cut-off

c. Costs of shipping, receiving inspection, inventory storage, and a portion of material control and handling costs.

d. Material utilization factors reflecting scrappage due to material removal and scrap due to damaged or inferior quality parts.

These items comprise the total raw material cost, which is then stated against the finished weight of the component. The lowest cost item, sheet stock for sheet design covers, was taken as a reference cost. The slope of the regression line for these data points was determined to be -0.23. The results of passing a line with this slope through the data point representing the reference cost is also shown in Figure 46. The value for RMC was determined by extrapolating this line to the intercept value at a weight of one pound. At one pound the value for aluminum was found to be $18.00 per pound. The reference cost, chosen as it was, is assumed to represent a utilization factor of one. This cost represents items a, b and c above. Using the same assumption regarding these items, and accounting for differences in mill prices (of sheet stock), an estimated value for RMC for titanium was determined to be $28.00 per pound. Adding this reference estimating line, assuming a constant cost-weight scaling, gives the results shown in Figure 47.

The next step was the development of the scrappage factors shown in Table 18. This was done independently by assessing the material utilization factor by component and by type of construction and material. Scrappage due to damaged or rejected parts was included. Some of the factors in this table were based on judgment due to the lack of specific data.

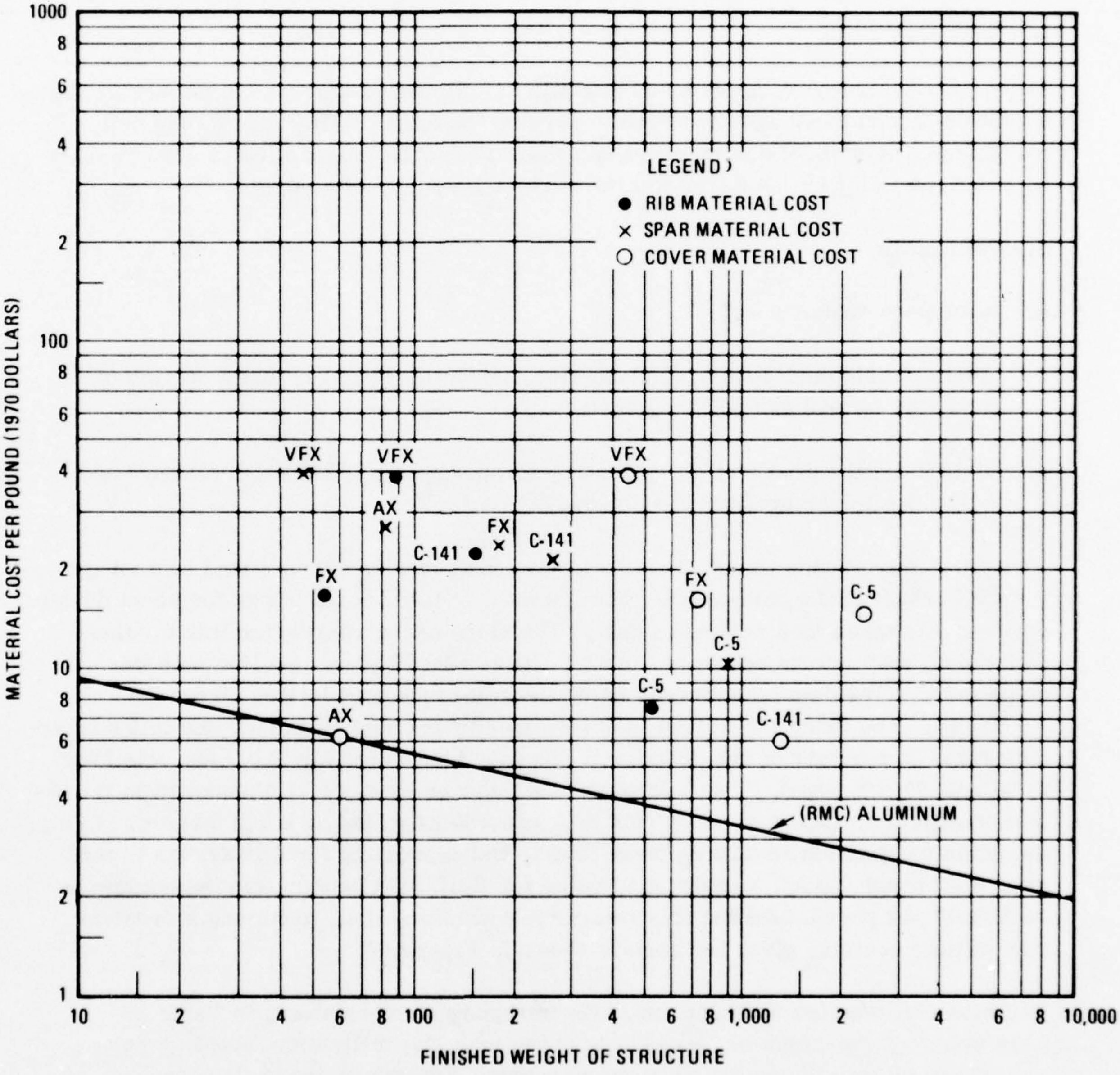


Figure 46. Ribs, Spar, and Cover Material Cost Data.

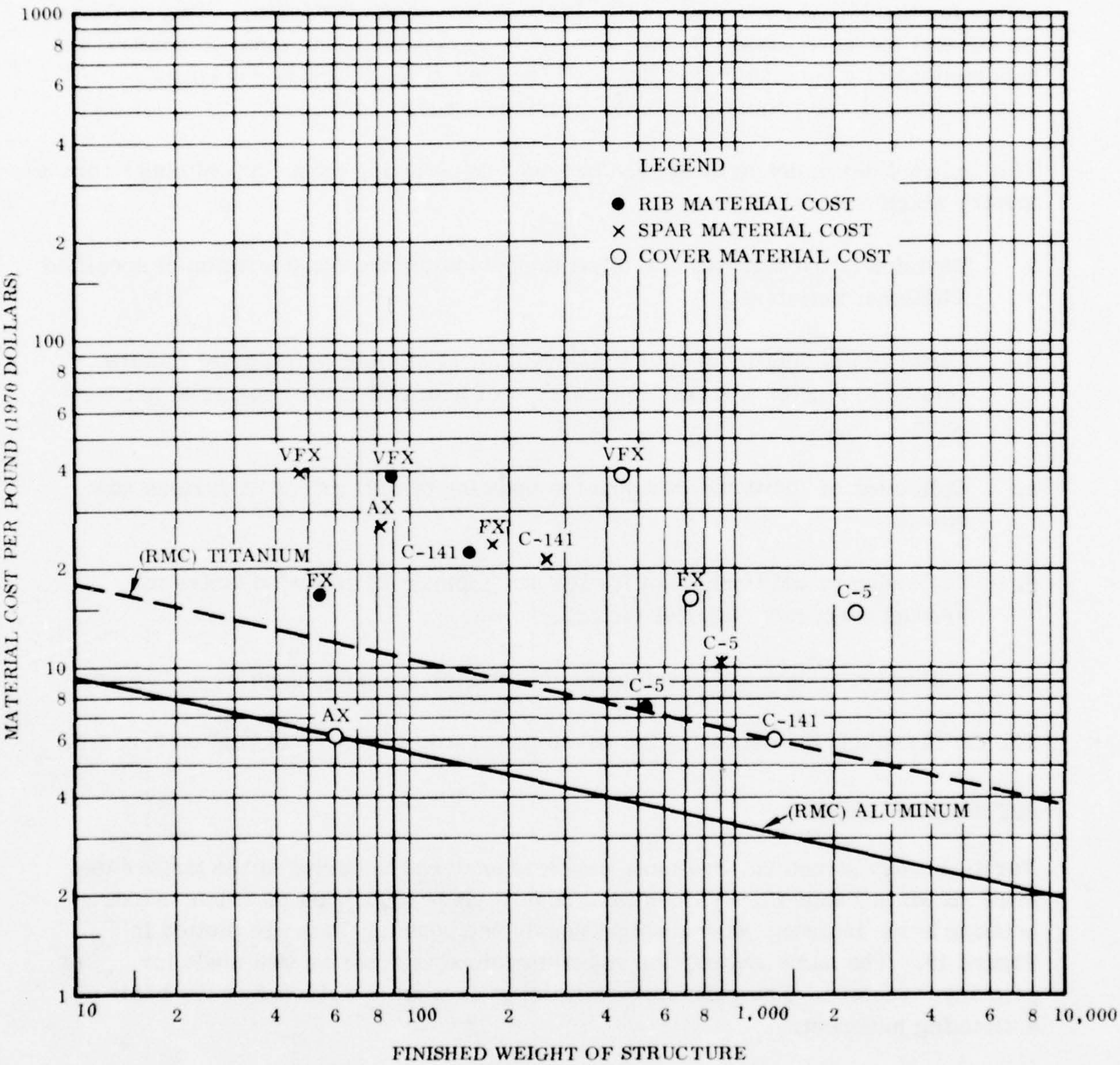


Figure 47. Rib, Spar, and Cover Cost per Pound Versus Structure Weight.

The original data was then normalized by dividing each datum by the appropriate scrappage factor. The results are shown in Figure 48. It is seen that all but three of the normalized values for aluminum fit the aluminum line, and also that the three normalized titanium points provide a good fit to the titanium reference line. The points for the FX rib, AX spar and C-141 spar are each off the line. Two of these, the FX and AX were based on estimates. The normalized data tends to confirm the assumptions of a constant value for G. Lines for graphite and boron epoxy composite material are retained from the previous study.

This original development of method provides the starting point for defining improvements, which are as follows:

a. Revision of the estimating method to provide for the consideration of specified additional variables.

b. Collection of additional data and development of yield (scrappage) factors related to type of construction and type of material and/or material product form.

c. Collection of additional data and the updating of mill prices of various new stocks.

d. Collection of additional data for the development of expanded tables for product form raw material factors.

e. Collection of data and development of a factor covering handling and usage.

The data base and the details of the development are discussed in Section 3.2.2.3.

<u>Secondary Structure</u>

For secondary structure, available data was analyzed to arrive at the factors that were shown in Table 19. (Values have been revised to correct an error in extrapolating to the intercept where weight equals one pound.) Data are plotted in Figure 49. The same assumption regarding slope is made as was made for primary structure. The reference estimating lines were selected on the basis of estimating judgment.

Secondary structure involves greater complexities in estimating material costs than was the case for primary structure. As can be seen by inspection of Figure 45, a wide variety of structural components is considered in the secondary structure categorization. Most of these components could in turn be broken down into parts, which, individually, are equivalent to the ribs, spars and covers of the primary structure.

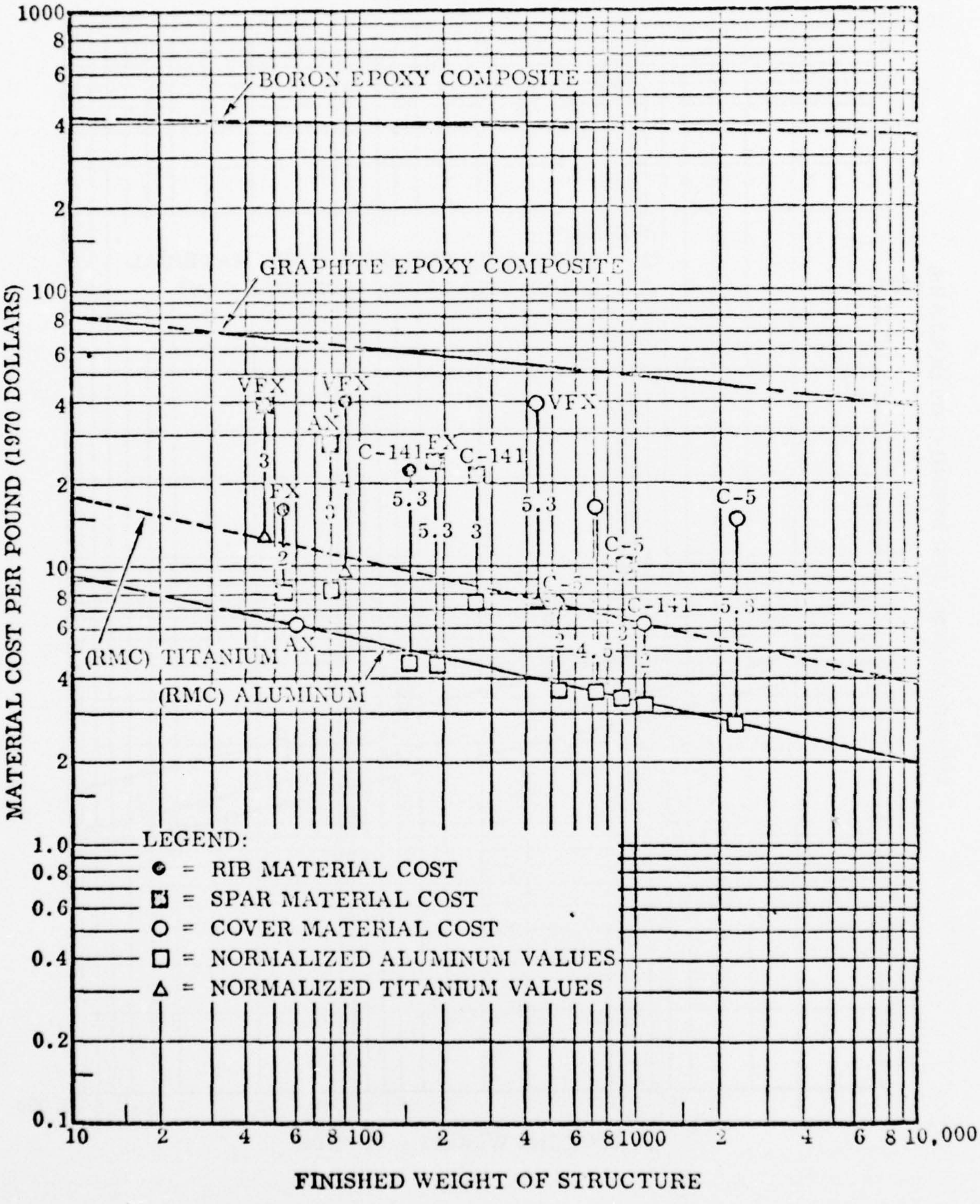


Figure 48. Rib, Spar, and Cover Cost per Pound Versus Structure Weight.

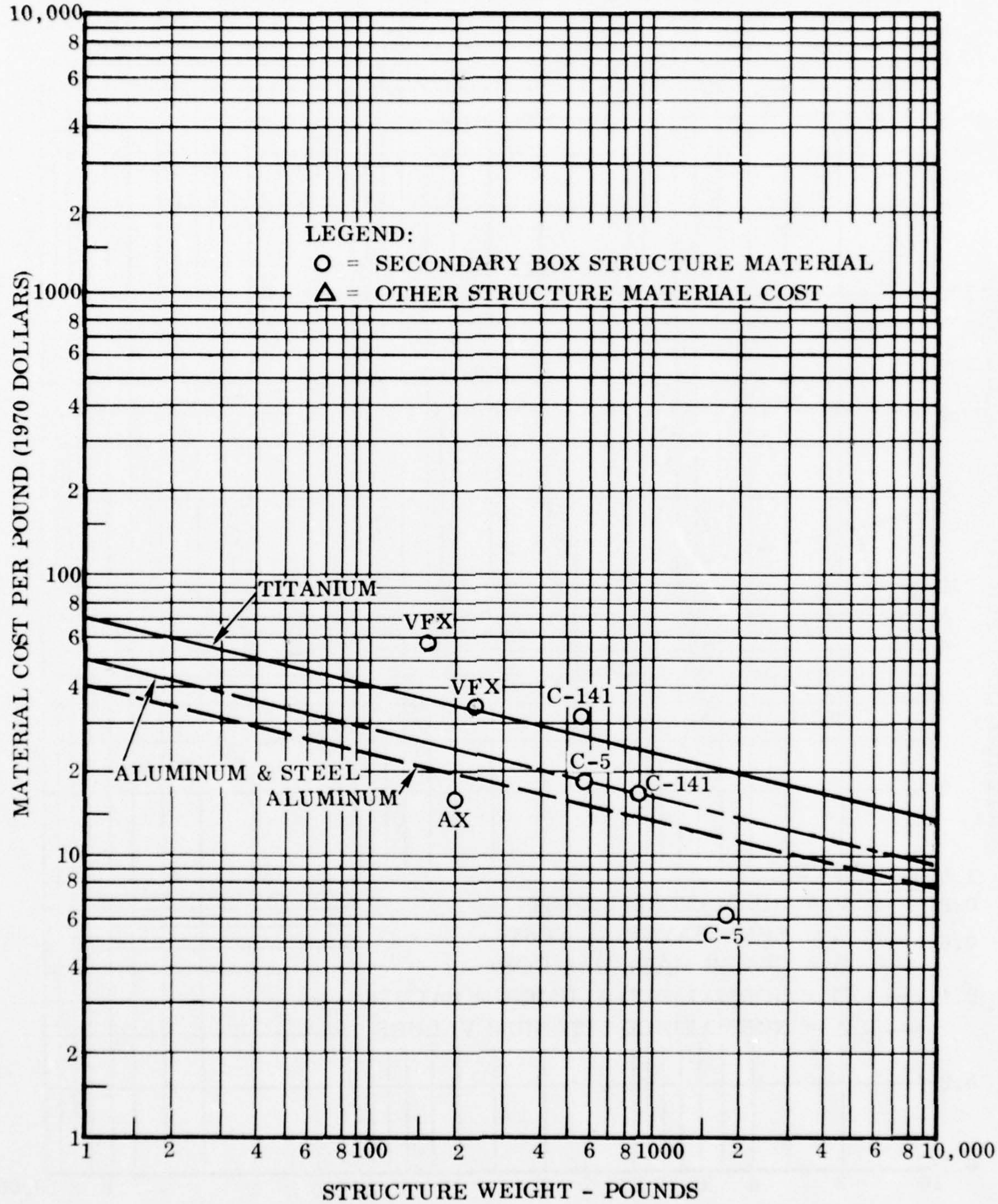


Figure 49. Secondary Box and Other Structure Cost Versus Structure Weight.

Estimating for secondary structure, vis-a-vis primary structure, is thus one level of identure higher. A further complexity is that the estimated costs of secondary structure material includes materials needed for the assembly of the component itself.

A comprehensive improvement of the secondary structure estimating method depends on the development of more detailed cost data and the development of supporting design synthesis programs. The determination of construction categories needs to be referenced to a systematic design definition, such as is provided by the structural synthesis program. In the absence of such definition, other categorization had to be established.

Improvements in estimating for secondary structure are to be approached as follows:

a. Development of additional cost data.

b. Analysis of this data to determine the effects of various materials and construction types.

c. Determination of suitable estimating factors: through new CERs, through redefinition of the terms in the existing CERs, or through the addition of new terms to the existing CERs.

In terms of level of detail, components such as leading edges and trailing edges are equivalent to the primary box. Categorizations of material and type of construction for secondary structure, therefore, are not applicable to primary structure.

3.2.2.3 Revised Estimating Methods.

Primary Structure

The revised estimating procedure that was developed is as follows:

$$\text{Cost} = (\text{Finished Weight})^{\text{Scaling}} \times \text{yield} \times \text{mill price} \times \text{form factor} \times \text{handling and usage factor}$$

In equational form this is:

$$M_i = W_i^G (SF_i) (MP_i) (FF_i) (UV) + \ldots + \ldots$$

where

M_i = material costs for various primary structure components, i.e., ribs, frames, spars, longerons and covers, with three separate terms for variations in type of construction and/or material by component.

W_i = finished weight of the component estimated

G = cost-weight scaling exponent

SF_i = yield (previously called scrappage factor)

MP_i = mill price by type of material

FF_i = form factor according to raw material and product form

UV = a factor to cover manufacturing usage variance

This form is similar to the one previously used, however, there are differences that need further explanation. The terms W and G are exactly as before. The scrappage factor, SF_i, is redefined to include only yield or utilization, excluding scrappage due to damaged or inferior quality parts. The excluded portion is included as part of the term UV, as explained below. The previously used term, RMC, is replaced by the terms, MP and FF. The first, mill price, has been separated out so that fluctuations in mill prices can be identified and input. The second, the form factor, represents the relationship between various raw material costs and accounts for differences attributable to the form of the product. These differences are judged to be reasonably constant. The term UV consists of a factor covering material handling costs and a usage factor covering losses attributable to damaged or inferior quality parts.

An objective of the study was to distinguish between scrap due to material removal and scrap due to damaged or inferior quality parts. Both enter into the buy-to-fly ratio but represent different effects. They are separated in the way that they are for two reasons: (1) Their cost is accounted for separately and (2) they represent different concepts. Scrappage, defined as yield (or utilization), represents the difference between design weight and planned buy weight and is determined by design features and material characteristics. Scrappage as represented by damaged or inferior quality parts, on the other hand, is a function of the manufacturing operation and is included in the combined allowance for manufacturing usage variance.

Yield

Material utilization is an important factor in determining the cost of a finished part. Utilization accounts for chips, trim, overage, offal, scrap, etc. The yield, or utilization factor, is applied to the finished weight of the various structural components to arrive at procured weight. This is a major portion of the conversion from fly-weight to buy-weight.

Table 21 provides values to be used for the term SF in estimating raw material cost. These values are based on study of information from various sources:

a. Contractor's experience

b. Sagamore conference data (Reference 5)

c. Miscellaneous studies

Table 21. Primary Structure Material Scrappage (Yield) Factor (SF)

		Aluminum	Steel	Titanium
Sheet		1.2	1.3	1.5
Billet		8.0	10.0	12.0
Forgings:	Conventional	5.0	7.0	12.0*
	Precision	1.11	2.0	4.5
Formed Extrusions		2.0	2.1	2.2
Plate		2.5	3.0	5.0
Bar and Rod		1.3	2.0	4.0
Tubing		1.3	1.5	2.0
Castings		2.0	3.0	-

*5° Die Forging

These values must be extrapolated in order to arrive at estimating inputs for alternative types of construction. If subsequent structural synthesis program improvements are achieved so as to provide a means of breaking down construction types into product form mixes, then Table 21 can be modified to state input values directly in terms of types of construction.

5. "Summary of Air Force/Industry Manufacturing Cost Reduction Study", AFML/TM-LT-73-1, January, 1973.

Mill Prices

Some data on mill prices are shown in the following tables and figures. Table 22 is a summary of available data. Figures 50 through 53 show plots of thickness versus cost per pound for aluminum sheet, aluminum plate, steel plate and titanium plate. In the case of titanium, if extremely thin material is neglected, a relationship can be determined as shown in Figure 53.

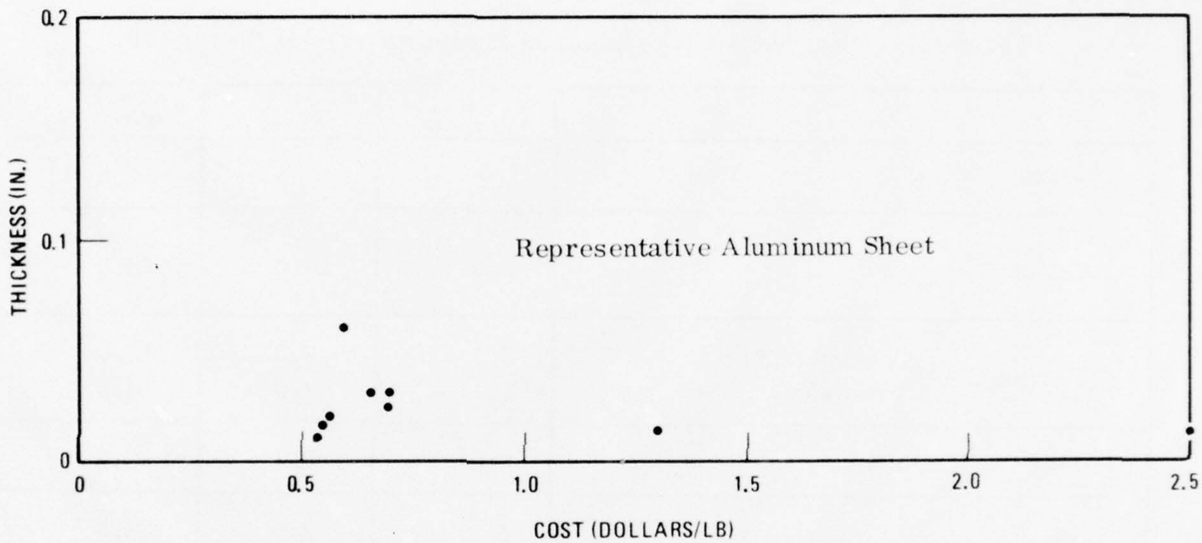


Figure 50. Cost Versus Thickness - Aluminum Sheet

Product Form

Product form has an effect on raw material cost. In general, the closer the procured material is to "net" form, i.e., the finished components, the more expensive it is. Intuitively, this seem justifiable, since part of the task of forming has been transferred to the material vendor. Varying amounts of offset in the in-hours labor is to be expected.

Form factors are given in Table 23. As indicated in the material estimating equation, this factor is applied to the mill price to arrive at what was formerly referred to as raw material cost, RMC. The net result is that the raw material cost factor is divided into two components: one related solely to material and the other related to product form.

Table 22. Mill Prices (MP). $/Lb

PRODUCT FORM	TYPE OF MATERIAL						
	Aluminum				Steel		
	2024	7050	Honeycomb Core	Titanium 6A1-4V	5629	10 N_i	
Sheet	$.993 - 1.19	$1.05 - 1.25	-	$5. - 16.(1)	$436 - 488/cwt	**109. - 122/cwt	
Billet	A1 2014 $2.50-$3.	2.25 - 2.75	-	8. - 10.	2.25 - **2.75	3.50 - ***4.00	
Forgings, conventional*	A1 2219 3.75-4.50	3.25 - 4.00	-	10. - 14.	2.50 - **3.25	4. - ***5.	
Castings: Investment	356 T6 $2.50 - $4.50	356T6 $3.50 - $6.00	-	$50. - 100.	17-4 Ph $6. - 25.	-	
Plate	.925 - 1.017	.988 - 1.08	-	$3.50 - 11.(1)	600-640/ cwt	$21.(1) **134- 146/cwt	
Bar	1.522 - 1.544	1.645 - 1.67	-	$8.60	6.(1) $6.50-7/ lb	150-160/ cwt	
Tubing	$76.92- $245.73/ c. ft.	$866.- $1726/ c. ft.	-	$150./ c. ft.	$6.50 - 35.	$7.30 ft.	
Core Material	-	-	(1) $3.25/ ft^2	-	-	-	
Extrusions	See Table 31 a						

*Precision forgings excluded
**321 Steel
*** 17-4 Steel
(1) AMAVS data

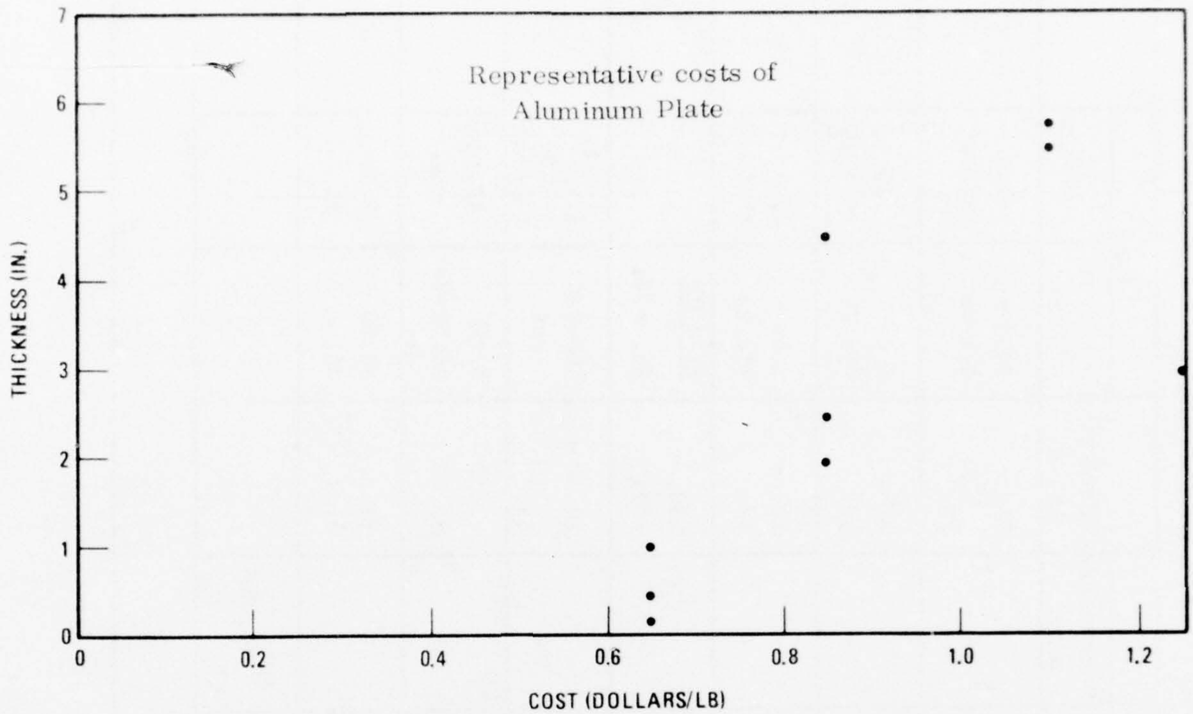


Figure 51. Cost Versus Thickness - Aluminum Plate

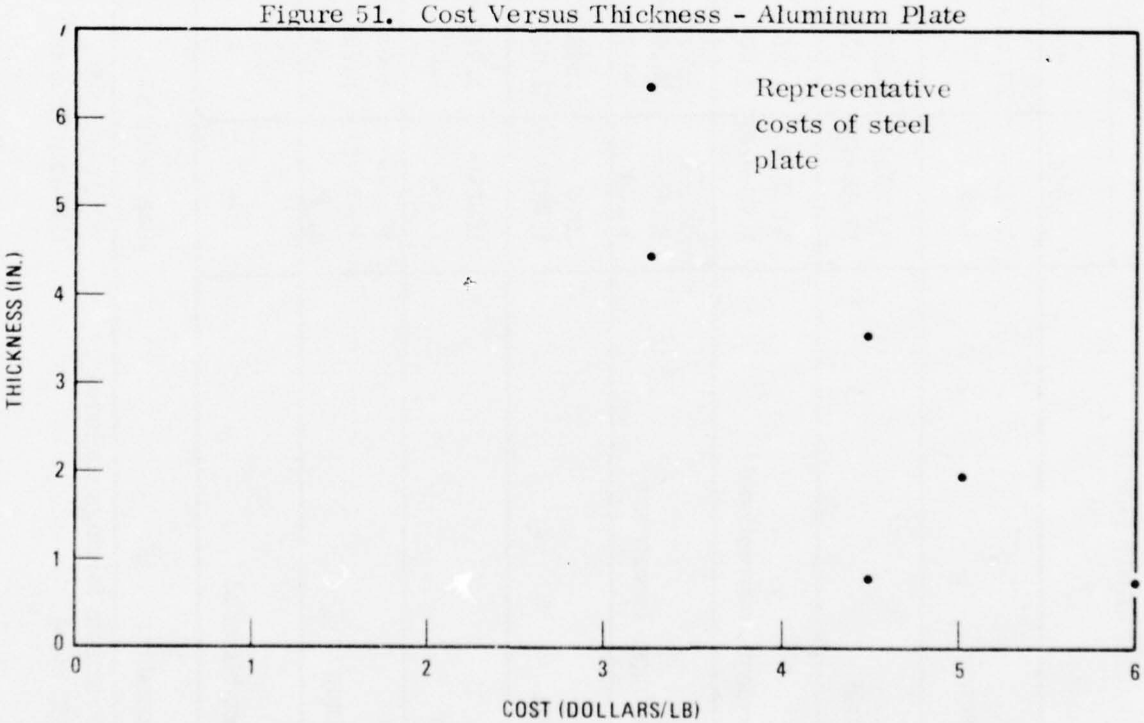


Figure 52. Cost Versus Thickness - Steel Plate

Table 23. Primary Structure Raw Material Product Form Factor (FF).

PRODUCT FORM	TYPE OF MATERIAL				
	Aluminum		Titanium	Steel	
	2024	7075	6A1-4V	5629	10 N_i
Sheet	1.0	1.25	5.-16.	5.	1.2
Billet	2.5 - 3.0	2.5	8. - 10.	3.	4.
Forgings: Conventional	4.0	3.7	10. - 14.	3.	4.5
Castings: Investment	4.0	5.0	50. - 100.	6. - 25.	-
Plate	1.0	1.0	3.5 - 11.	6.	2. - 10.
Bar	1.5	1.7	8.	6.5	2.
Tubing	-	-	-	-	-
Extrusions	-	-	-	-	-

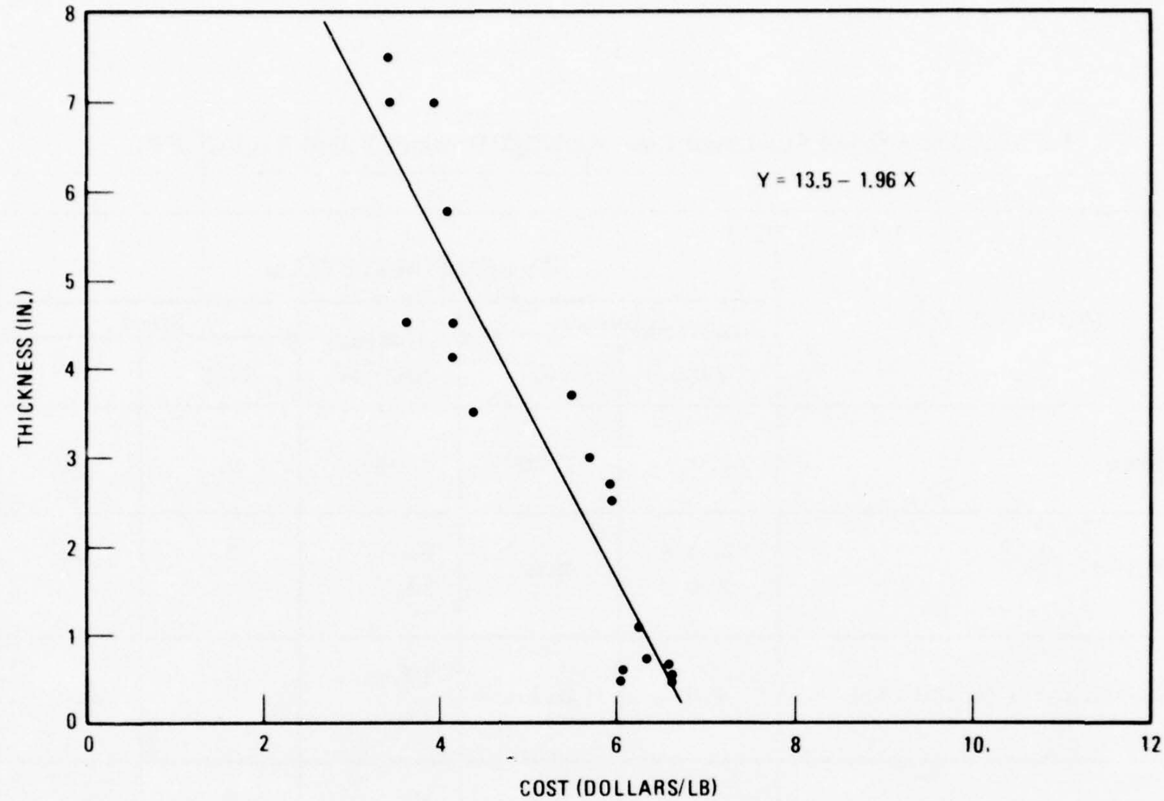


Figure 53. Cost Versus Thickness - Titanium Plate

Usage Variance

In the contractors estimating practice, a manufacturing usage variance is applied that covers scrappage and excess usage in addition to a number of other items the most significant of which are freight-in, freight out, surpluses, repair, gains and losses, and obsolete material. This variance factor, as estimated for raw material commodities, is approximately 20%, applied to estimated material cost. Scrap and excess usage make up the largest fraction of this and are the items of interest in this study. They may be expected to vary to some extent due to material and type of construction. Combined, they make up approximately 65% of the 20%, or 13% against estimated structural material cost.

Since usage variance covers a number of things, no attempt has been made in past practice to identify variations in scrappage attributable to type of construction or type of material. Suggested values based on engineering judgment are given in Table 24. These values are percentages that are to be added to the residual percentage considered not to be variable.

Table 24. Material Usage Values

TYPE OF CONSTRUCTION	Material		
	Aluminum	Titanium	Steel
Ribs, Spars, Frames, Longerons:			
Built-Up Web Stiffener	13%	20%	16%
Built-Up Truss	13%	20%	16%
Sheet Web (Roll Formed)	11%	17%	14%
Corrugated Web	12%	18%	15%
Integral Web Stiffener	10%	20%	16%
Integral Truss	10%	20%	16%
Covers:			
Built-Up Skin Stringer	13%	20%	16%
Integral Skin Stringer	10%	20%	16%
Machined Plate	10%	20%	16%
Sheet	10%	18%	12%
Sandwich Bonded & Beaded	15%	---	16%

Evaluation of the Term G

Hardware elements that are primary structure, or analogous to primary structure, were selected from the AMAVS data base and are plotted in Figure 54. These data are summarized in Table 25. A regression equation relating material cost per pound to finished structure weight was developed as shown in Figure 54. This can be compared to the regression of material cost to finished weight shown in Figure 48.

The two data bases represented by these figures are combined as shown in Figure 55. The regression equation based on these data is also shown. This result can easily be interpreted as a value of 1.0 for the term G. This value is suggested pending contrary results, especially since it agrees with the assessment of experienced cost estimators. The term G will be retained in the estimating function, however, to provide for possible future reconsideration.

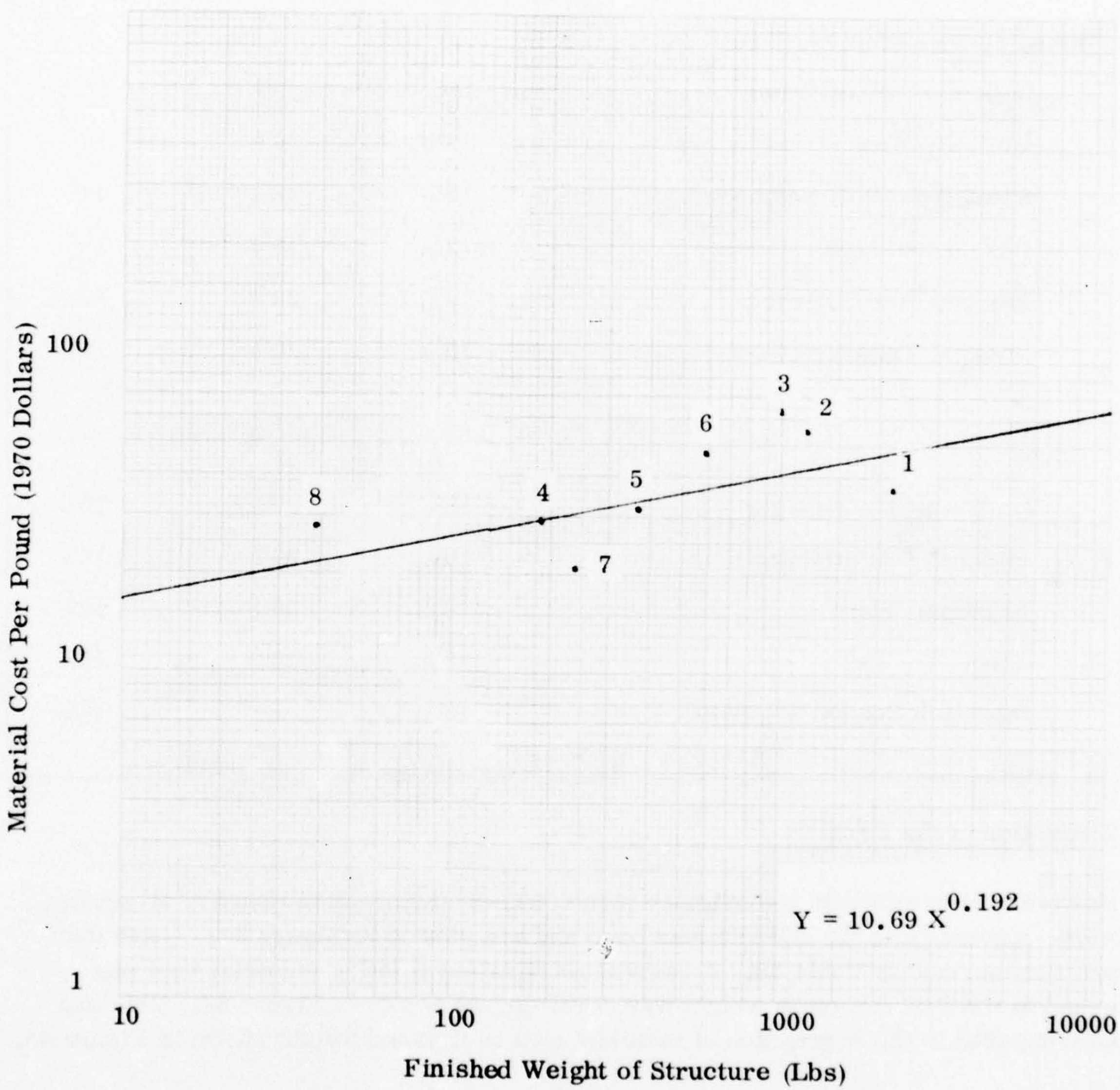


Figure 54. Material Cost by Structural Weight - AMAVS Components.

Table 25. AMAVS COMPONENTS DATA BASE

	AMAVS COMPONENT		Rib		Frame		Cover (Aero Surface)		Longeron	
			Wt.	$/Lb	Wt.	$/Lb	Wt.	$/Lb	Wt.	$/Lb
1	Upper Cover Assembly	4010					2216	37.41		
2	Forward Bulkhead	4080	1200	56.17						
3	Aft Bulkhead	4060	1011	62.45						
4	Centerline Rib	4110	189	29.10						
5	X_F39 Rib	4120	378	30.79						
6	Closure Rib Installation	4030	586	47.97						
7	X_F84 Rib	4130	239	20.50						
8	Rib, Pivot Lug Y_F 944.15	*4006	70	20.00						
9	Longerons (4110)	4118							39	28.00

*Not included in the regression

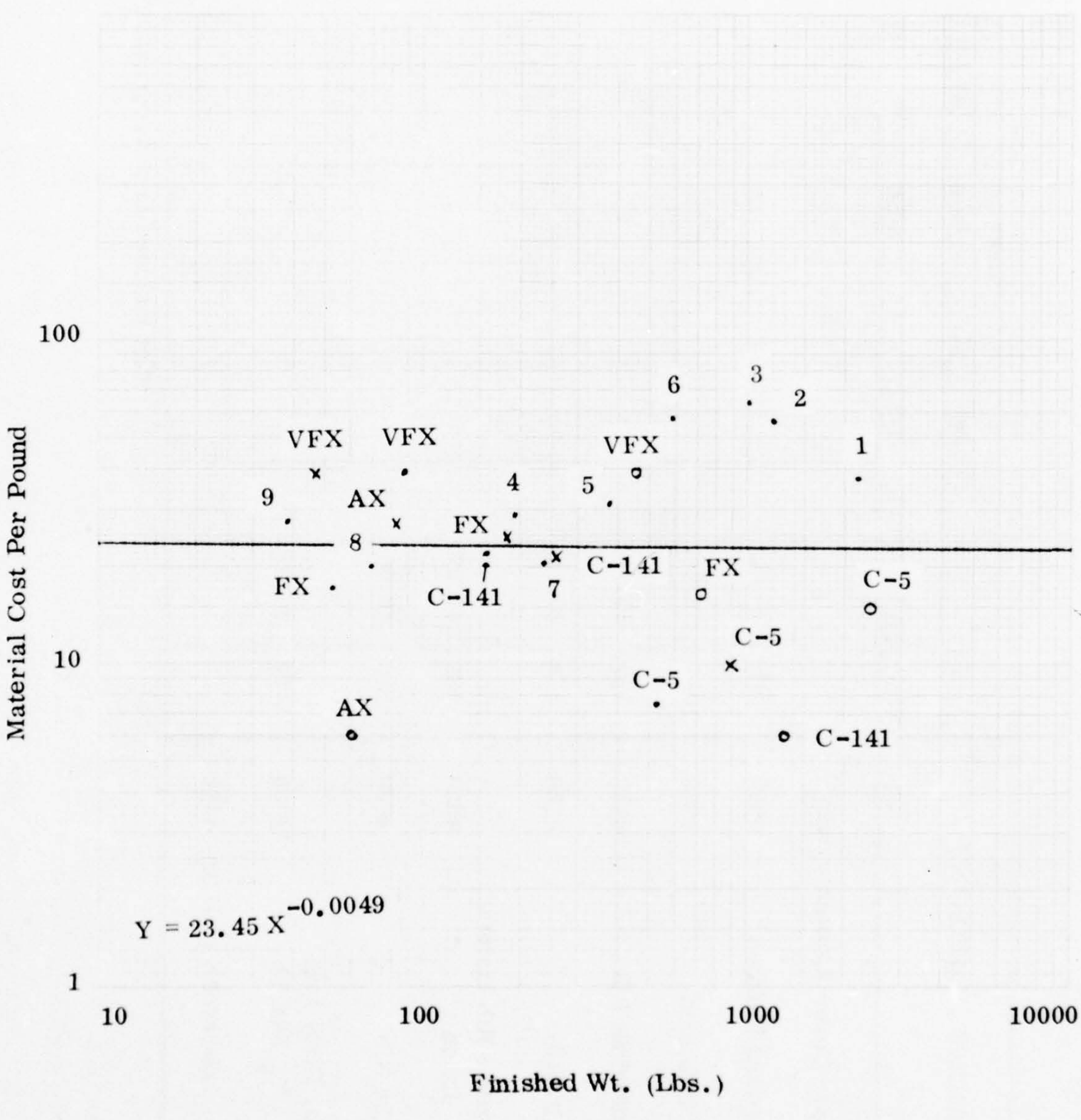


Figure 55. AMAVS Data and Reference 1 Data.

Secondary Structure

Two approaches to estimating the material cost of secondary structure were investigated. The first of these is a modified version of the one used for primary structure. The second uses finished weight as the cost related variable but applies to that a cost per pound factor that accounts for type of construction, material, yield, scrapped parts, and handling in an empirical manner from plots of data analogs.

The form based on the primary structure method is shown below. The need for modification arises because of the previously mentioned fact that secondary structure is analyzed at a higher level of indenture than is primary structure.

$$M_i = WD_i^G (SFS_i) (MC_i) (HUS)$$

where WD and G are as previously defined and where

M_i	=	total material cost for secondary structure components,
SFS	=	a value for yield that is a composite value for the secondary structure component.
MC	=	material cost: a composite value based on component material mixes
HUS	=	factor for handling and usage based on a composite picture of the component.

Individual values for each of these terms is required by component. This task can be simplified, however, since the list of components can be reduced by an appropriate categorization. Each term is explained in the discussion that follows.

The term SFS has the same meaning as in the case of primary structure, except that for secondary structure the value specified for yield represents an average value based on a mix of components. These mixes do not lend themselves to convenient categorization so that value selection is subjective to a considerable degree. A typical procedure for determining a given value is to relate the elements of the given structural component to analogous primary structure elements and to develop a correspondingly weighted factor. Weighting is accomplished on the basis of the finished weight of the component.

The term MC is a combination of the terms MP and FF, mill price and product form factor, respectively, used for ordinary structure. Because secondary structure is estimated at a higher level than is primary structure, the development of a

weighted mill price seems especially difficult with results expected to be somewhat ambiguous. The combined term is, therefore, used in the estimating equation. The development of values of MC, however, still takes into consideration the idea of mill price and product form variations.

The term HUS is analogous to HU. Both are empirically derived averages. As was seen for primary structure, this term includes an allowance for scrapped parts. Some variation in its value can be expected, but relative to the total, this is small and will be neglected.

The second approach to estimating the material cost of secondary structure is based on a relationship as illustrated in Figure 56 of the following form:

$$Y = ax^{b}$$

where

Y = material dollars per pound

a = estimating coefficient: the value of Y @ x = 1

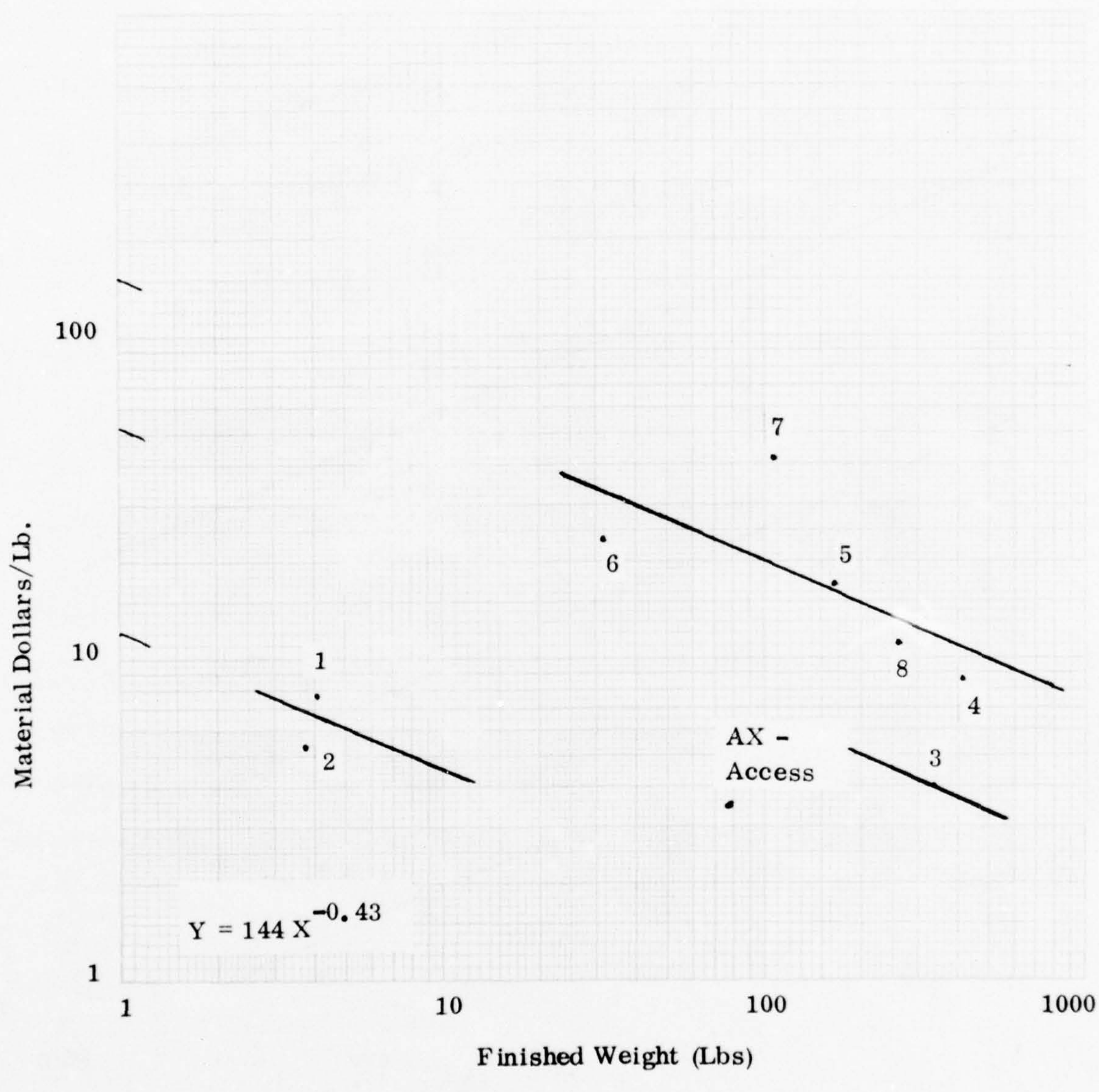
x = finished weight of the component

b = weight-cost scaling relationship

Data from Reference 5 was plotted and analyzed with the results shown in Figures 56 through 60. The upper curve in Figure 56 and 58 and the single curve in Figure 59 are based on regression snalysis. The curves in Figure 57 are visually fitted using the same slope as in Figure 56. Figure 60 is miscellaneous data evidencing no fit. Where a slope is established by regression, the same slope is used for each of the other curves shown in that figure. A summary of results is given in Table 26 comprising intercept values, slopes, and information descriptive of the complexity of each component. Each data point is identified in Table 27.

In view of the above results, the second method is recommended. This considers that with this method the estimating of labor for secondary structure components is accomplished in a consistent manner at a consistent level of detail.

Having chosen this approach, additional data was collected and analyzed and estimating coefficients and analogs were developed. Data are from the contractor's data base as shown in Table 28. These data are plotted on the previous charts where applicable, otherwise plots are made on Figures 61 and 62.



Estimating Coefficient: $12/Lb

Complexity factors: 12:52:144 or 1, 4.33, 12.

Figure 56. Material Cost by Structural Weight - Doors

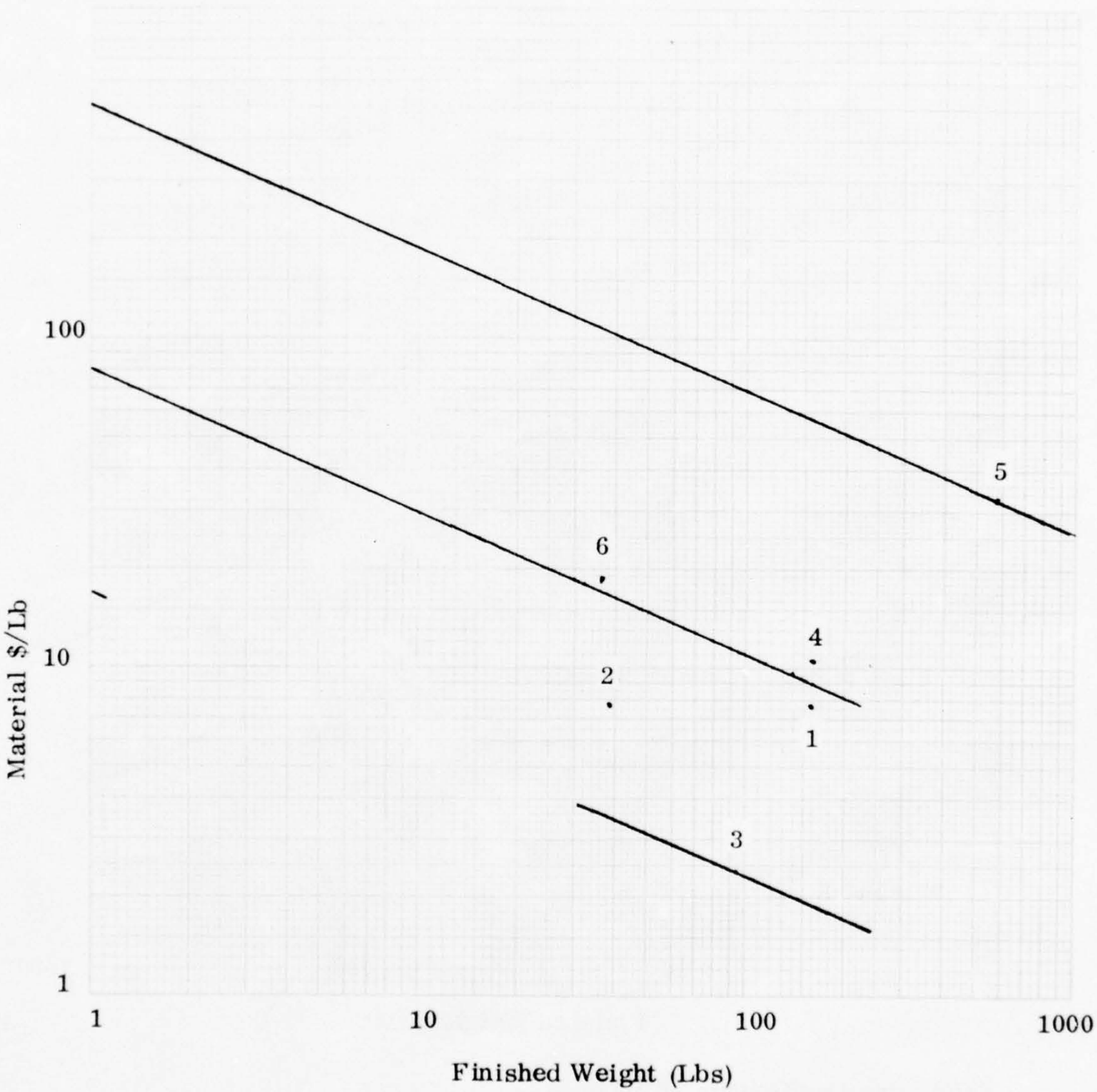


Figure 57. Material Cost by Structural Weight - Air Ducts and Tail Cones.

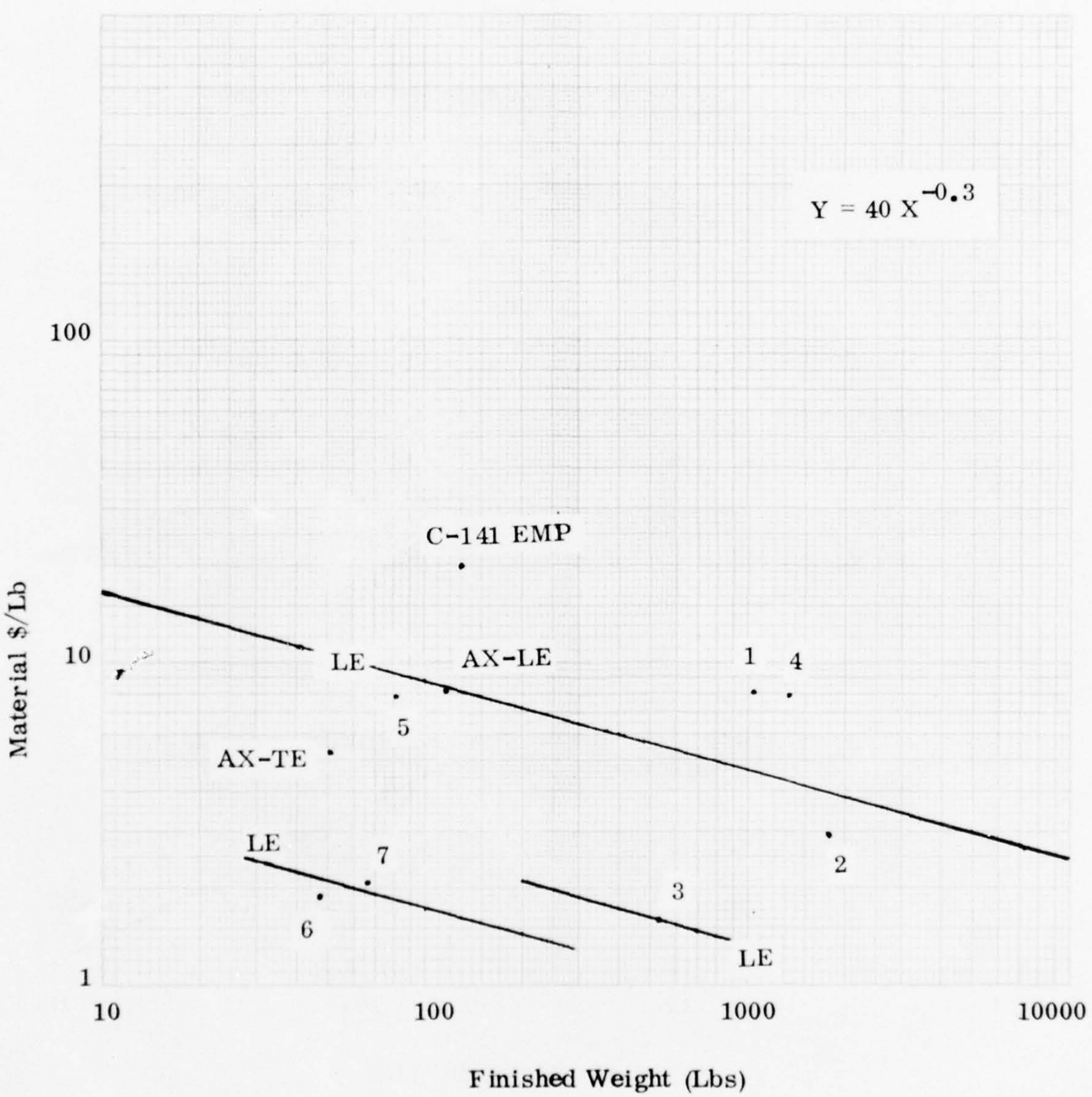


Figure 58. Material Cost by Structural Weight - Leading Edges, Trailing Edges.

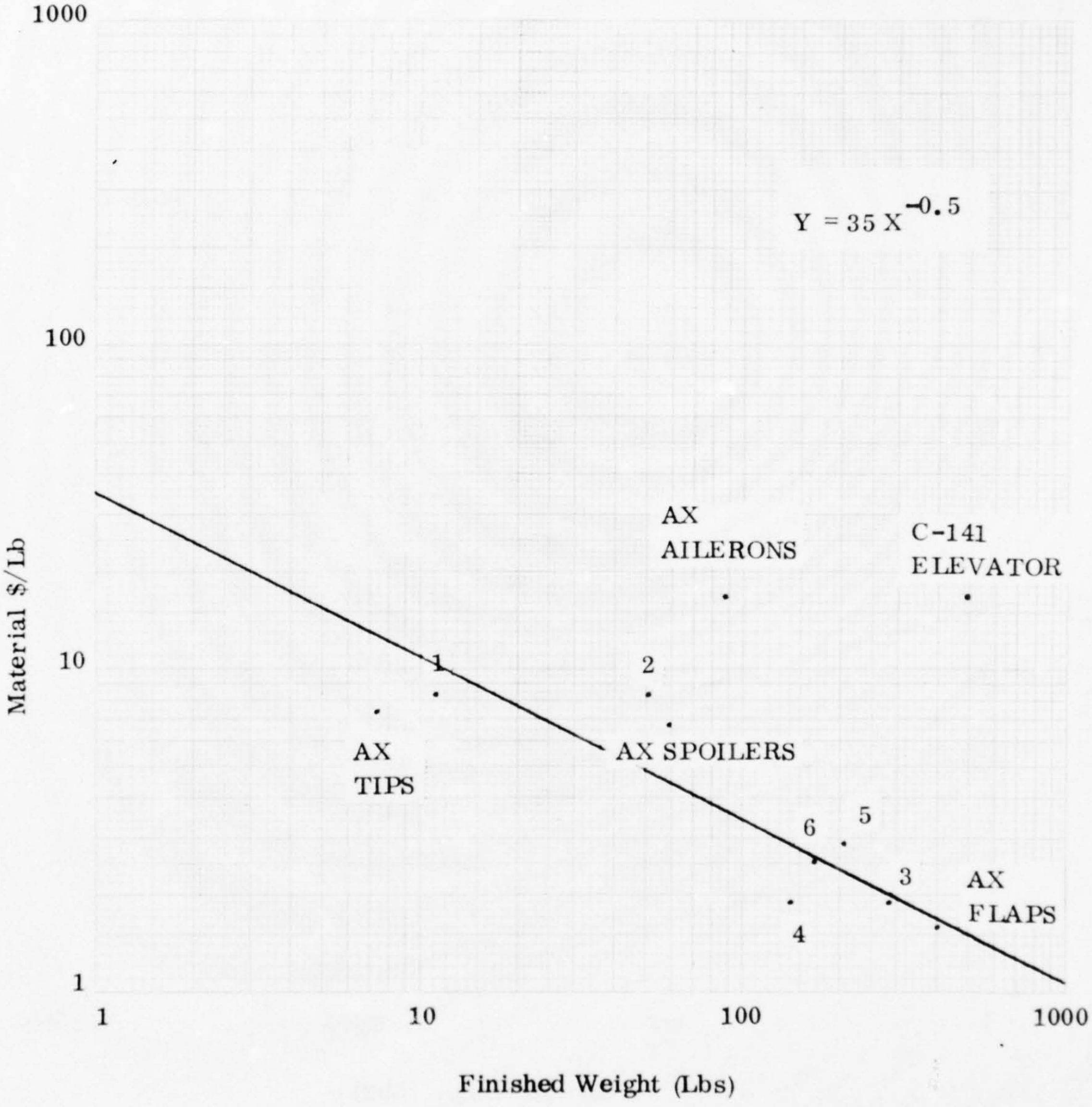


Figure 59. Material Cost by Structural Weight - Control Surfaces.

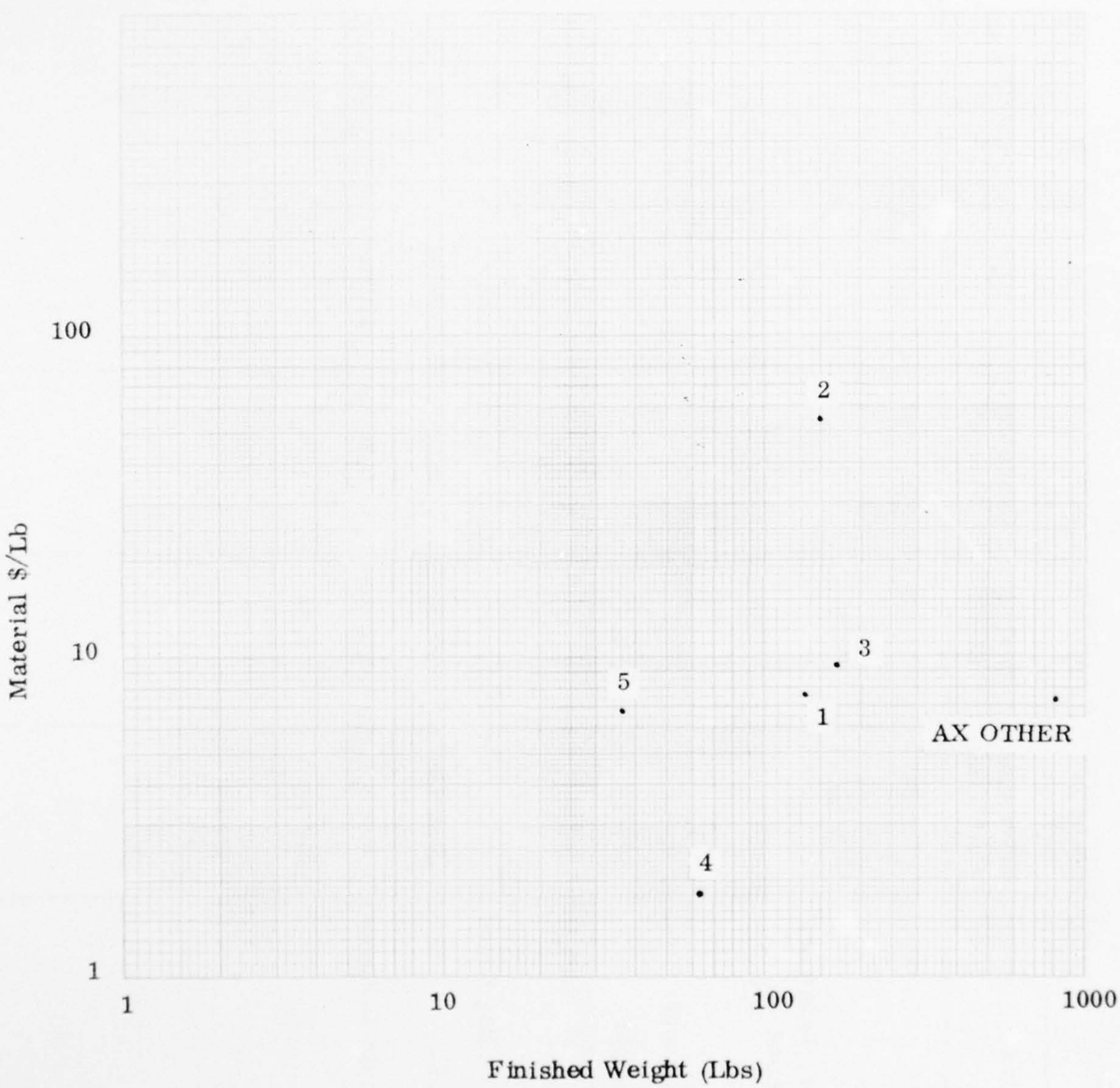


Figure 60. Miscellaneous Components Material Costs.

Table 26. **Secondary Structure Estimating Factors for Material Estimating.**

COMPONENT	Estimating Coefficient	Scaling Slope	Complexity Factor	NOTES
Doors:				
Access	$12/Lb	-0.43	1.	
Pressure Door, Transport			4.33	
Bonded Honeycomb			12.00	
Actuated H/C			26.67	
Air Ducts and Tail Cones:				
Tail Cone - Simple	$17/Lb	-0.43	1.	
Tail Cones - Complex			4.7	
Air Intake Duct			29.4	
Leading Edges - Trailing Edges				
Empennage L.E.	$6.8/Lb	-0.30	1.	Bonded
Wing L. E.			1.5	
Wing, Empennage L.E.			5.9	Military
Control Surfaces	$35/Lb	0.50	1.	

Table 27. Secondary Structure Estimating Factors Data Base

	Finished Weight (Lbs.)	Material Cost	Material $/Pound
Doors:			
1. Access Door, S/M-B/U*	4.1	31.5	7.7
2. Access Door, S/M-B/U	3.8	20.	5.3
3. Pressure Door, Transport	341.	1380.	4.0
4. M.L.G. Door, Bonded H/C	420.	3620.	8.6
5. Unactuated Door, Bonded H/C	168.	2856.	17.0
6. L/G Door, Bonded H/C	32.	760.	23.8
7. Actuated Door, Bonded H/C	109.	4597.	42.2
8. Cowl Panel, Bonded H/C	265.	2990.	11.3
Air Ducts and Tail Cones:			
1. Duct Assy, S/M-B/U	159.7	1220.	7.6
2. Tail Cone Assy, S/M-B/U	38.1	292.	7.7
3. Tail Cone, S/M-B/U	94.	226.	2.4
4. Nose Cowl, S/M-B/U	161.	1665.	10.3
5. Air Intake Duct, S/M-B/U	586.	19500.	33.3
6. Tail Cone, F/G-B/U	36.	675.	18.8
Leading Edges - Trailing Edges:			
1. Wing L/E, S/M-B/U	1056.	8640.	8.2
2. Wing L/E, S/M-B/U	1800.	5220.	2.9
3. Wing L/E, S/M-B/U	531.	873.	1.6
4. Empennage L/E, S/M-B/U	1370.	10850.	7.9
5. Empennage L/E, S/M-B/U	82.	648.	7.9
6. Empennage L/E, S/M-Bond	48.	91.	1.9
7. Empennage L/E, S/M-Bond	68.	146.	2.1
Control Surfaces			
1. Spoiler, S/M-B/U	11.3	95.	8.4
2. T.E. Flap	53.2	448.	8.4
3. Flap	290.	537.	1.9
4. Rudder, S/M-B/U	142.	264.	1.9
5. Elevator, S/M-B/U	209.	606.	2.9
6. Aileron, S/M-B/U	170.	450.	2.6
Miscellaneous Components:			
1. Speedbrake, S/M-B/U	135.3	1034.	7.6
2. Canopy, Casting	150.	8390.	55.9
3. Canopy, S/M-B/U	170.	1600.	9.4
4. Wing Tip, S/M-B/U	63.	112.	1.8
5. Wing Tip, F/G	37.	252.	6.8

Table 28. Component Data Base

COMPONENT	Material $/Lb.	Finished Weight (Pounds)	Material Cost
C-141 Empennage			
Leading Edge-Horiz. & Vertical Stabilizer	$19.80	131.	2594.
Bullet, Aft	20.95	92.	1927.
Elevators	16.66	496.	8264.
Rudder		217.	
Bullet, Forward	19.83	92.	1824.
A-X			
Leading Edge	8.06	117.8	949.
Trailing Edge	5.31	52.	276.
Ailerons	16.83	89.2	1501.
Tips	7.33	7.5	55.
Spoilers	6.65	58.5	389.
Flaps	1.60	408.8	654.
Support Fittings			648.
Access Doors	3.56	78.	278.
Other	7.28	812.	5915.
F-111 SDO Components			
Ferry Wing Tip	16.00	69.	$1104.
600 Gallon Tank	5.00	544.	2720.
Fixed Cowl and Blow-In Doors	9.00	570.	5130.
Fiberglass Side & RAM Panels	9.00	196.	1764.
SRAM Pivot Pylon	20.00	325.	6500.
Stabilization Boom	5.00	165.	825.
Weapon Bay Fuel Tanks	13.00	310.	4030.
Fixed Armament Pylon	6.00	381.	2286.
Fixed Fuel Pylon	9.00	263.	2367.
Pivot Fuel Pylon	20.00	115.	2300.
Forward Electronic Bay	8.00	475.	3800.
Aft Center Fuselage	8.00	998.	7984.
Spike Assembly	17.00	241.	4097.

Axles, Trunnions, Fittings

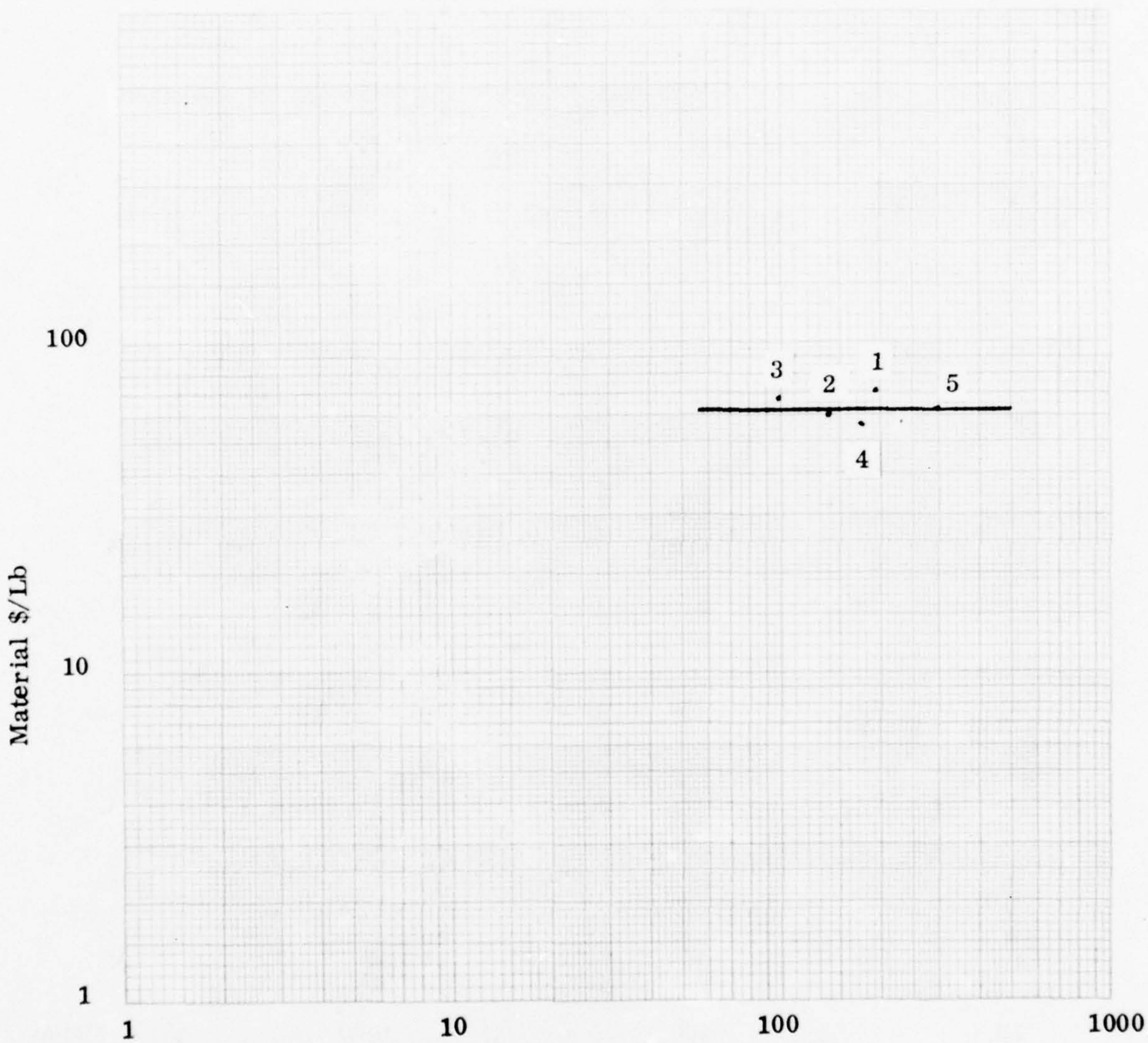


Figure 61. Material Cost by Structural Weight - Axles, Trunnions, Fittings.

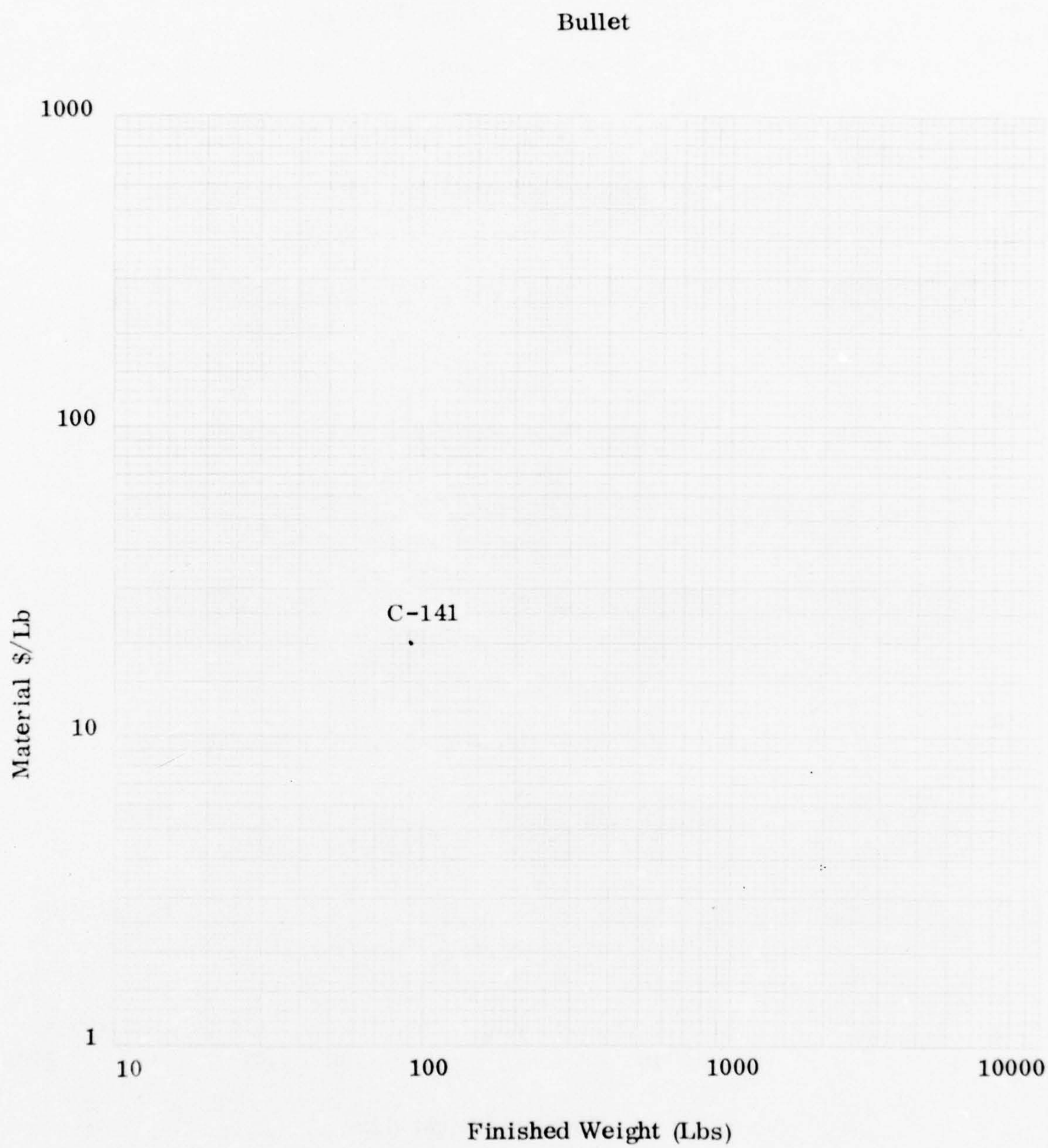


Figure 62. Material Cost by Structural Weight - Bullet Fairing.

3.3 ASSEMBLY CER MODIFICATION

3.3.1 REVIEW OF EXISTING ASSEMBLY CERs. Under the existing method, assembly costs are estimated by a series of CERs in a sequence as shown in Figure 63. This represents a generalized concept of the assembly process developed for modeling purposes. In the real world, assembly operations may vary from this idealized concept. This concept assumes that ribs, spars, covers (primary structure components) are assembled as units, that these are assembled as a structural component (wing, stabilizers, fuselage, nacelles), that primary assembly occurs in one step followed by major mate of the major components.

It will clarify the discussion to digress for a moment to define the assembly terms as they are being used:

Subassembly comprises bench assembly and other assembly not using an operation and inspection log (OIL) and not requiring an assembly fixture.

Major Assembly comprises assembly controlled by inspection log and accomplished in an assembly fixture.

Primary Assembly involves the installation, assembly and check of functional subsystem components.

Major Mate is the tying together of the major structural components.

Final assembly is not included, although it is a step in the assembly process, since it is related to the entire aircraft, including engines and avionics.

The existing assembly CERs are referenced in Figure 63 by the numbers appearing in parenthesis. These are reviewed below in connection with a discussion of their modification. Each is a part of the existing, computerized, cost model, estimating logic. Inputs are categorized by the computer program, and the nature of the various inputs is made clear by the CER descriptions. The numbering system corresponds to that contained in Reference 1. Omitted numbers in the sequence are for non-assembly CERs.

3.3.2 APPROACH TO CER MODIFICATION. Modification of the CERs to accomplish the objectives stated previously was approached in the following way:

a. Determine whether any revisions in the assembly sequence model are required and what interaction occurs at the detailed CER level.

b. Identify the changes that will occur in each of the individual CERs due to the different assembly techniques under study.

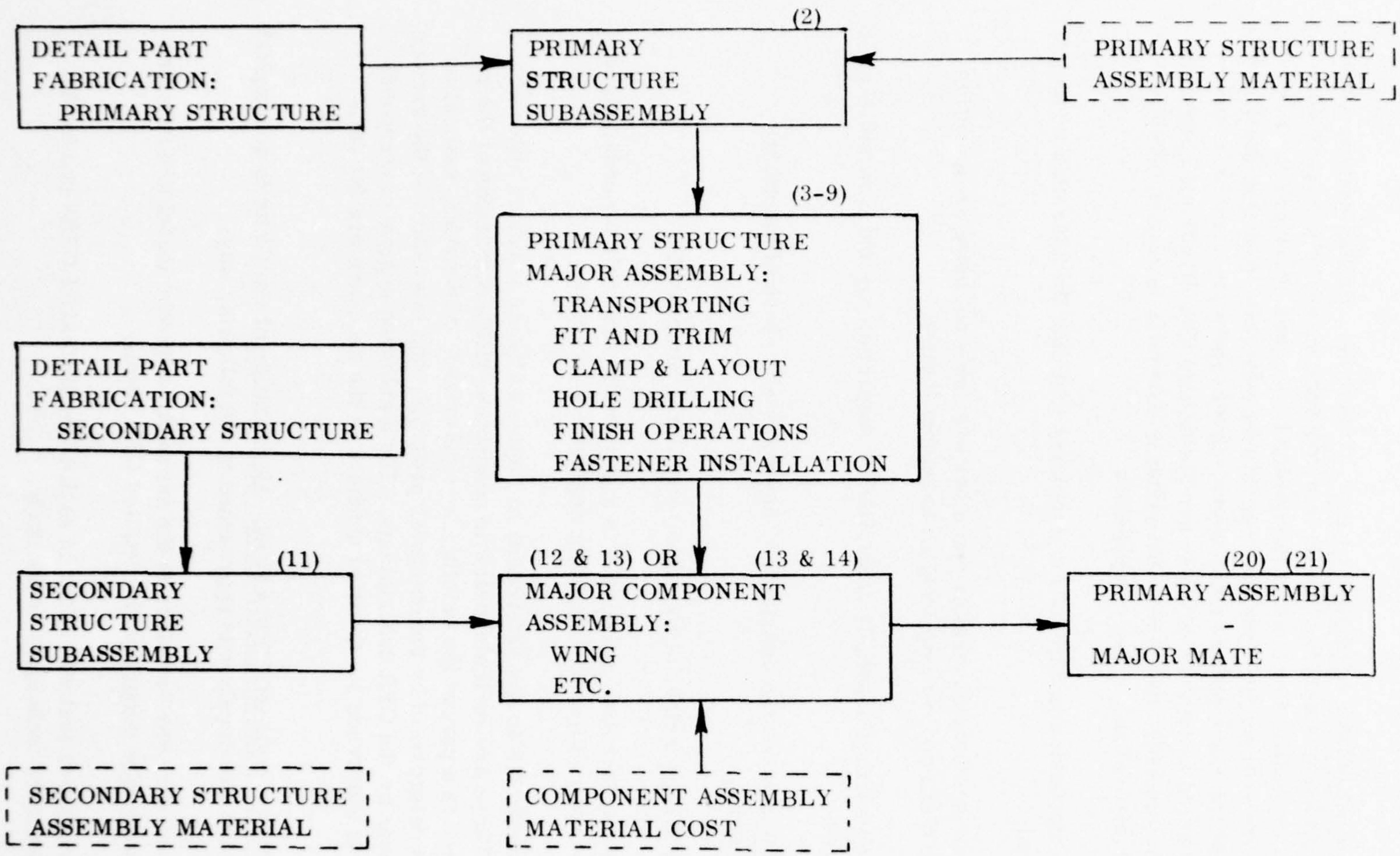


Figure 63. Assembly CER Sequence

c. Quantify changes using historical cost data, as available, augmented by estimating judgments.

d. Modify input data tables to reflect the above changes.

3.3.2.1 Impact of Assembly Alternatives on Assembly Sequence Model. Figure 63 shows the model used for estimating assembly costs. It depicts the breakdown into steps and gives their sequence. It is to be determined whether this model will serve equally well for the four alternative assembly techniques under study: automatic riveting, interference fit fasteners, diffusion bonding and adhesive bonding. The answer lies in the fact that we are dealing with a model abstraction, which serves for any of the alternative techniques. At least this is true for the current degree of usage for each. Automatic riveting can be expected to increase the times when components such as rib caps and spar caps are assembled directly onto a skin rather than being assembled into a separate rib or spar. Adhesive or diffusion bonding would have a similar effect, although these processes could be applied at either a subassembly or major assembly level. Use of interference fit fasteners would have little effect on the model, as such. The major effect, and that which is to be considered, occurs within each individual CER. This is analyzed and discussed in the following section.

3.3.2.2 CER Analysis. The questions investigated in each case consisted of the following, answered for each of the four alternative assembly techniques:

a. Is the present form of the CER still adequate and can the added techniques be accommodated solely by changes to the estimating coefficients and/or estimating factors?

b. If not, which terms are affected, and how is this to be handled?

SUBASSEMBLY HOURS FOR RIBS, FRAMES, SPARS, LONGERONS AND COVERS

$$H_i = \left[\frac{W_i\, CM_i + W_i\, CM_i + W_i\, CM_i}{WT_i} \right] (HF_i)\, (WT_i)^{E_i} \qquad (2)$$

where

H_i = subassembly hours for ribs, frames, spars, longerons and covers corresponding to variable inputs

W_i = weights used for detail fabrication

CM_i = a series of complexity factors corresponding to component type related to subassembly

WT_i = summation of weights

HF_i = a series of reference cost per pound values for ribs, frames, spars, longerons, and covers related to subassembly labor

E_i = a series of weight scaling exponents for ribs, frames, spars, longerons, and covers related to subassembly labor

The CER is designed to permit the handling of up to three kinds of ribs, spars or covers. This is accomplished by means of the first term,

$$\left[\frac{W_i\ CM_i + W_i\ CM_i + W_i\ CM_i}{WT_i} \right],$$

which is a weighted complexity factor taking into account the different complexity of each component entered. The weights entered are a characteristic of the design and are to be obtained from a weight estimate.

The term HF represents a baseline, historical cost for a selected type of material and construction. The term CM is a complexity factor that quantifies the effect of alternative types of material or construction. With suitable modification of these last two terms, the basic CER for primary structure subassembly hours can be retained.

The operation of this CER can be further clarified by reference to Figure 64 (A similar discussion has been provided for detail fabrication). If we start with the available data base as shown, the problem is to fit a CER to these data and to determine the values of the terms CM, HF and E. The scaling exponent, E, has been derived from historical data as a value of approximately 0.67 for a total hours curve, or -0.33 on an hours per pound basis. This is approximately an eighty percent slope. The term HF is the hours per pound value at W = one pound, which must be determined for estimating purposes. Complexity is quantified in terms of type of construction and type of material (as is illustrated, for example, in Table 29).

In the original development of the method, it was assumed that normalization of the data with respect to complexity would produce adjusted data points evidencing good correlation between cost and weight. A best fit curve of these data (further assumed to have a slope of -0.33) would indicate the value of H at the W = 1 lb intercept on a log-log plot.

Normalization by independently developed complexity factors taken from Table 38 (see Reference 1) produces the adjustments shown in Figure 65. The types of construction and material involved in the data shown are described in Table 30. In the cases where more than one type of construction is involved, an approximate weighting is used: 3 to 1 by weight for built-up to integral for the C-141 horizontal stabilizer and 3 to 1 by weight for integral web to sheet web for the VFX horizontal stabilizer. The A-X components require no adjustment since the type of construction is the reference point

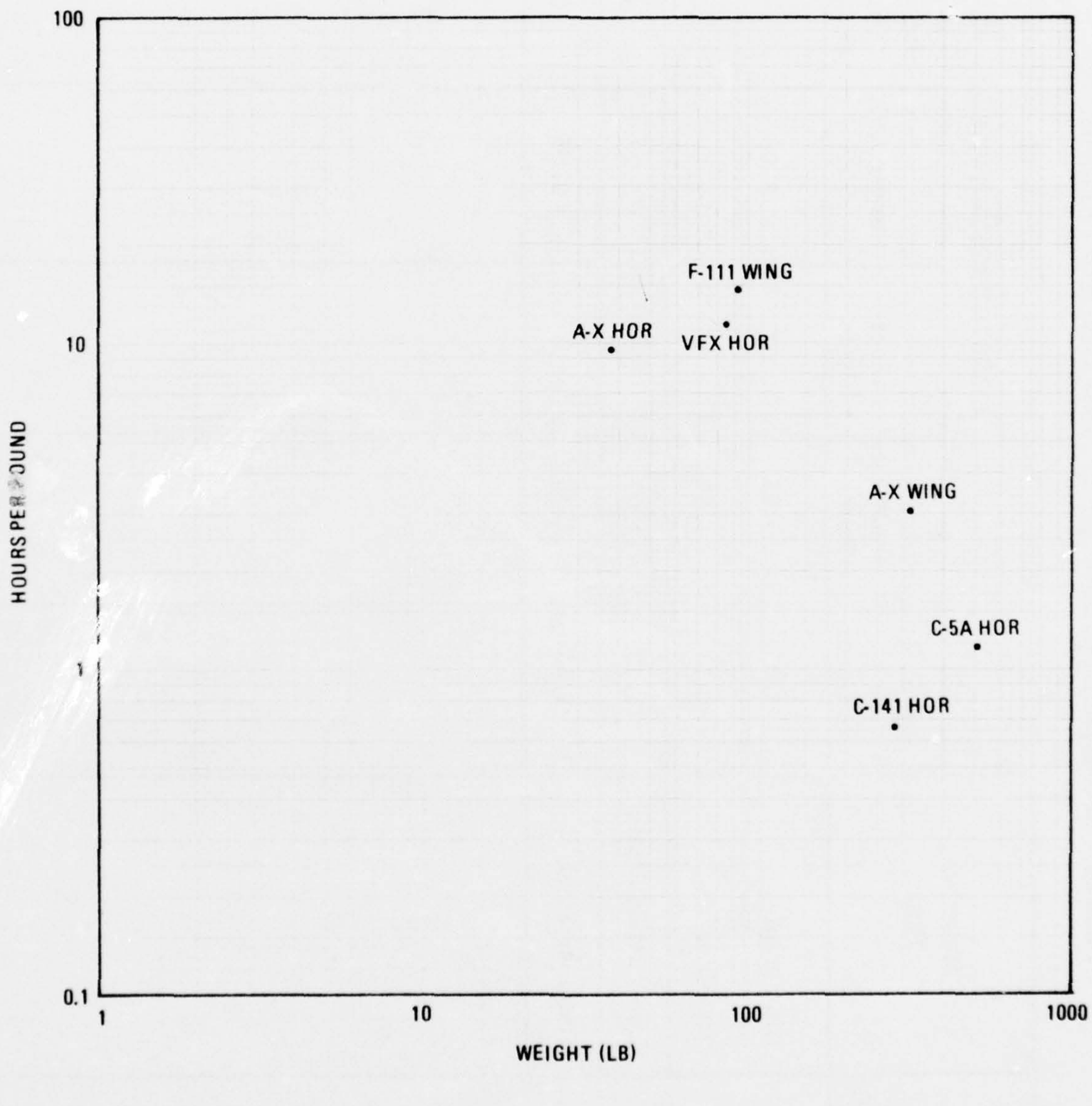


Figure 64. Rib Subassembly Hours Per Pound Against Weight
(Figure F-7 in Reference 1)

Table 29. Aerodynamic Surfaces Rib Complexity Factors - Subassembly

Structural Element CER Input Symbol	Material Type	CONSTRUCTION TYPE					
		Built-Up Web Stiffener	Built-Up Truss	Sheet Web	Corrugated Web	Integral Web Stiffener	Integral Truss
Ribs, Sub-Assembly CM_1	Aluminum	1.00	0.89	0	2.08	0	0
	Titanium	1.75	1.57	0	2.58	0	0
	Low Carbon Steel	1.19	1.07	0	2.22	0	0
	Stainless Steel	2.33	2.10	0	2.98	0	0

Table 30. Rib Subassembly by Material and Construction Type

Aircraft/Component	Type of Construction	Type of Material
C-141 Horizontal Stabilizer	Built Up and Integral Truss	Aluminum
C-5A Horizontal Stabilizer	Built Up Truss	Aluminum
A-X Wing	Built Up Web Stiffener	Aluminum
A-X Horizontal Stabilizer	Built Up Web Stiffener	Aluminum
VFX Horizontal Stabilizer	Sheet Web and Integral Web Stiffener	Titanium
F-111 Wing	Integral Truss	Aluminum

with an assigned complexity of one. The F-111 wing and the VFX horizontal represent anomalies as far as complexity is concerned because this assembly task was predicted as zero. The explanation for this is that in the actual data, the necessary hand finishing for the machining operation (classified as detail fabrication) is considered as assembly. This is an unresolved discrepancy as far as the complexity factors are concerned because the amount of handfinishing is unpredictable.

The resulting data still exhibits a great deal of scatter. This is typical of data at a detailed level. A choice of parameters other than weight does not improve the correlation.

The selection of a value for HF then, is done by analogy. Maintaining the assumption of a constant value for the scaling exponent, a curve is drawn thru the most nearly analogous component; and the reference cost per pound is that shown for W = 1 lb. Complexity then is determined by an additional analysis. It is evident then that a generalization of complexity factors requires a broader data base.

The HF value currently in the computer model is that depicted in Figure 65 by A: a value for subsonic aircraft of 14.5 hours per pound at a weight of one pound. The complexity factors shown in Table 29 for conventional structure were applied to that baseline for the demonstration test case described in Reference 1. Since the A-X components are built-up web stiffeners, the most nearly analogous baseline reference is B. This gives a value for HF of 26 hours per pound to which the complexity factors would then be applied.

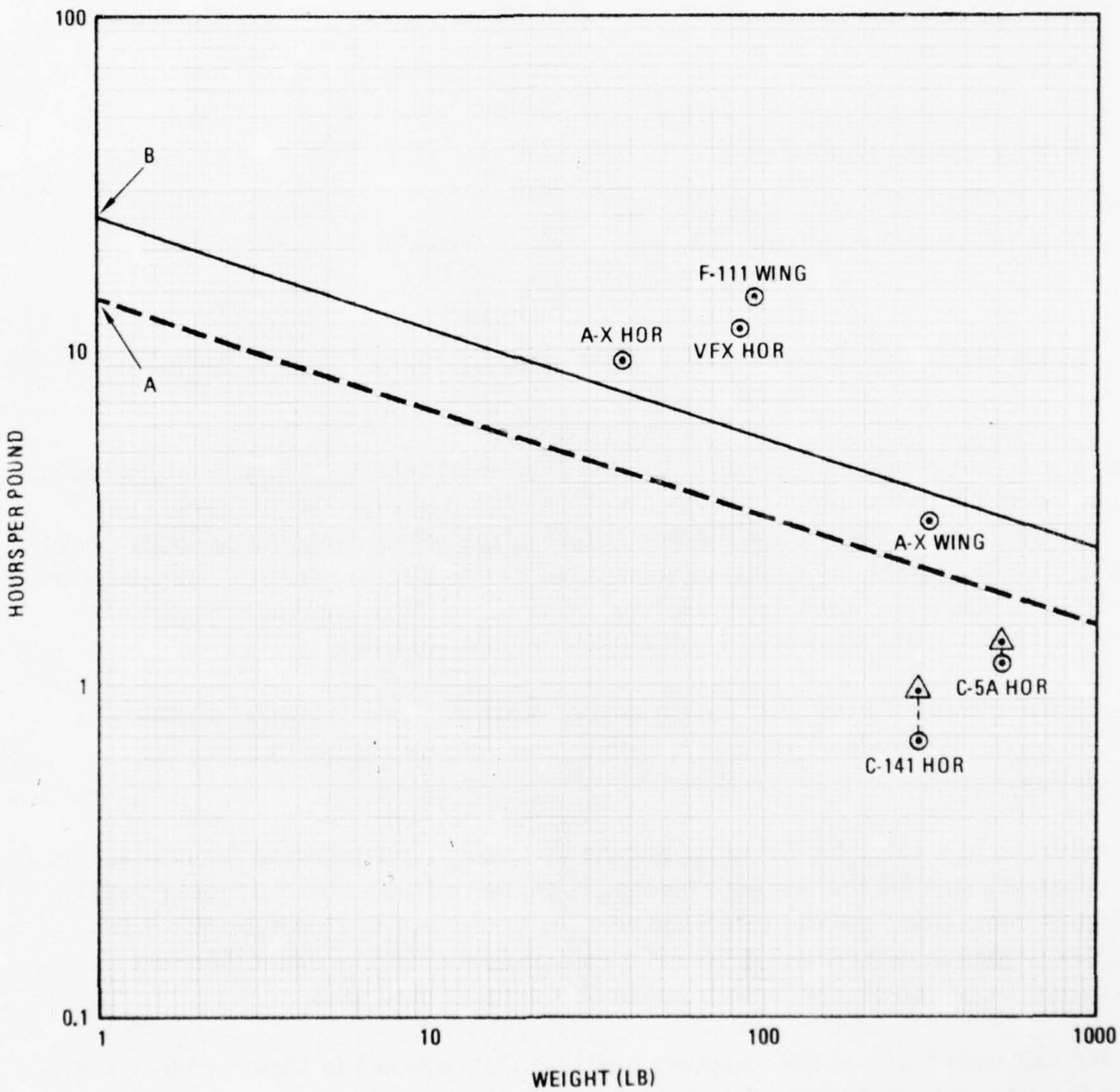


Figure 65. Rib Subassembly Hours Per Pound Against Weight

Completion of the CER analysis requires review of the previously developed complexity factors and development of expanded tables to include factors for advanced assembly techniques. The resulting factors are shown in Tables 31 through 36. The supporting reference estimating factors are derived in Figures 66 through 70 and summarized in Table 37.

3.3.2.3 Factor Development. Factors for interference - fit fasteners were determined by means of an Industrial Engineering time study. Conditions under which the time study was made were established by Manufacturing Research. The work was done at bench level by shop personnel in connection with an ongoing manufacturing project. The times shown in Table 38 are the result of that study. Each listing is based on the installation of one hundred 3/16" fasteners. Times are given in actual decimal hours.

Table 38. Interference-Fit Fastener Effects

	Steel Hi-Lok	Titanium Hi-Lok	Steel Hucks	Titanium Hucks
Insert in Hole	.0009	.0012		.0013
Insert & Tap in Hole			.0011	
Seat - Drive Flush	.0010	.0014		.0016
Seat - Low Press. Pull			.0006	
Nut on & Tighten - Air	.0014	.0014		
Collar On & Set - Pull				.0012
Collar On & Hi Press Pull			.0013	
Total Decimal Hours	.0033	.0040	.0030	.0041

The factors for interference fit are determined as follows: In Table 38 data, the seating operations constitute the added effort associated with interference-fit fasteners. The ratio of total hours to totals hours less these hours indicates the magnitude of the added fastener installation task. These ratios are given in Table 39.

Table 39. Adjusted Hours Ratios

	Steel Hi-Lok	Titanium Hi-Lok	Steel Hucks	Titanium Hucks
Total Decimal Hours	.0033	.004	.003	.0041
Adjusted Hours	.0023	.0026	.0024	.0025
Ratios	1.43	1.54	1.25	1.64

Table 31. Aerodynamic Surfaces - Ribs, Complexity Factors for Subassembly (CM)

Type of Construction		MATERIAL			
		Aluminum	Titanium	Low Carbon Steel	Stainless Steel
Built-Up Web Stiffener	Conventional	1.0	1.75	1.19	2.33
	Automatic riveting	.73	1.277	.868	1.700
	Interference - fit fasteners	1.154	2.019	1.373	2.688
	Diffusion bond riveting	.86	1.505	1.023	2.003
	Weldbonding	.93	1.627	1.106	2.166
Built-Up Truss	Conventional	0.89	1.57	1.07	2.10
	Automatic riveting	.712	1.255	.855	1.679
	Interference - fit fasteners	.993	1.751	1.193	2.343
	Diffusion bond riveting	.801	1.412	.962	1.889
	Weldbonding	.845	1.490	1.015	1.993
Sheet Web	Conventional	—	—	—	—
	Automatic Riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	-	—	—	—
Corrugated Web	Conventional	2.08	2.58	2.22	2.98
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Integral Web Stiffener	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Integral Truss	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—

Table 32. Fuselage - Frames and Bulkheads, Complexity Factors for Subassembly (CM)

Type of Construction		MATERIAL			
		Aluminum	Titanium	Low Carbon Steel	Stainless Steel
Built-Up Web Stiffener	Conventional	1.0	1.75	1.19	2.33
	Automatic riveting	.73	1.277	.868	1.700
	Interference - fit fasteners	1.154	2.019	1.373	2.688
	Diffusion bond riveting	.86	1.505	1.023	2.003
	Weldbonding	.93	1.627	1.106	2.166
Built-Up Truss	Conventional	0.89	1.57	1.07	2.10
	Automatic riveting	.712	1.255	.855	1.679
	Interference - fit fasteners	.993	1.751	1.193	2.343
	Diffusion bond riveting	.801	1.412	.962	1.889
	Weldbonding	.845	1.490	1.015	1.993
Sheet Web	Conventional	—	—	—	—
	Automatic Riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Corrugated Web	Conventional	2.08	2.58	2.22	2.98
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Integral Web Stiffener	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Integral Truss	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—

Table 33. Aerodynamic Surfaces - Spars, Complexity Factors for Subassembly (CM)

Type of Construction		MATERIAL Aluminum	Titanium	Low Carbon Steel	Stainless Steel
Built-Up Web Stiffener	Conventional	1.0	1.72	1.2	2.31
	Automatic riveting	.66	1.135	.792	1.524
	Interference - fit fasteners	1.194	2.053	1.432	2.758
	Diffusion bond riveting	.83	1.427	.996	1.917
	Weldbonding	.91	1.565	1.092	2.102
Built-Up Truss	Conventional	1.2	1.52	1.28	1.77
	Automatic riveting	.80	1.013	.853	1.180
	Interference - fit fasteners	1.425	1.804	1.519	2.101
	Diffusion bond riveting	.996	1.261	1.062	1.469
	Weldbonding	1.092	1.383	1.164	1.610
Sheet Web	Conventional	—	—	—	—
	Automatic Riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	-	-	-
	Weldbonding	—	—	—	—
Corrugated Web	Conventional	3.84	5.4	4.22	6.75
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Integral Web Stiffener	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Integral Truss	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—

Table 34. Fuselage - Longerons, Complexity Factors for Subassembly (CM)

Type of Construction		MATERIAL			
		Aluminum	Titanium	Low Carbon Steel	Stainless Steel
Built-Up Web Stiffener	Conventional	1.0	1.72	1.2	2.31
	Automatic riveting	.66	1.135	.792	1.524
	Interference - fit fasteners	1.194	2.053	1.432	2.758
	Diffusion bond riveting	.83	1.427	.996	1.917
	Weldbonding	.91	1.565	1.092	2.102
Built-Up Truss	Conventional	1.2	1.52	1.28	1.77
	Automatic riveting	.80	1.013	.853	1.180
	Interference - fit fasteners	1.425	1.804	1.519	2.101
	Diffusion bond riveting	.996	1.261	1.062	1.469
	Weldbonding	1.092	1.383	1.164	1.610
Sheet Web	Conventional	—	—	—	—
	Automatic Riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Corrugated Web	Conventional	3.85	5.4	4.22	6.75
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Integral Web Stiffener	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Integral Truss	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—

Table 35. Aerodynamic Surfaces - Covers, Complexity Factors for Subassembly (CM)

Type of Construction		MATERIAL Aluminum	Titanium	Low Carbon Steel	Stainless Steel
Built-Up Skin Stringer	Conventional	1.0	2.24	1.33	3.22
	Automatic riveting	.68	1.523	.904	2.189
	Interference - fit fasteners	1.186	2.656	1.577	3.818
	Diffusion bond riveting	.84	1.881	1.117	2.704
	Weldbonding	.92	2.060	1.223	2.962
Integral Skin Stringer	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Machined Plate	Conventional	—	—	—	—
	Automatic Riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Sheet	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—
Sandwich	Conventional	3.5	-	-	-
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	-	-	-	-
	Weldbonding	—	—	—	—

Table 36. Fuselage - Skin Panel, Complexity Factors for Subassembly (CM)

Type of Construction		MATERIAL			
		Aluminum	Titanium	Low Carbon Steel	Stainless Steel
Built-Up Skin Stringer	Conventional	1.0	2.24	1.33	3.22
	Automatic riveting	.68	1.523	.904	2.189
	Interference - fit fasteners	1.186	2.656	1.577	3.818
	Diffusion bond riveting	.84	1.881	1.117	2.704
	Weldbonding	.92	2.060	1.223	2.962
Integral Skin Stringer	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Machined Plate	Conventional	—	—	—	—
	Automatic Riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Sheet	Conventional	—	—	—	—
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—
Sandwich	Conventional	3.5	-	-	-
	Automatic riveting	—	—	—	—
	Interference - fit fasteners	—	—	—	—
	Diffusion bond riveting	—	—	—	—
	Weldbonding	—	—	—	—

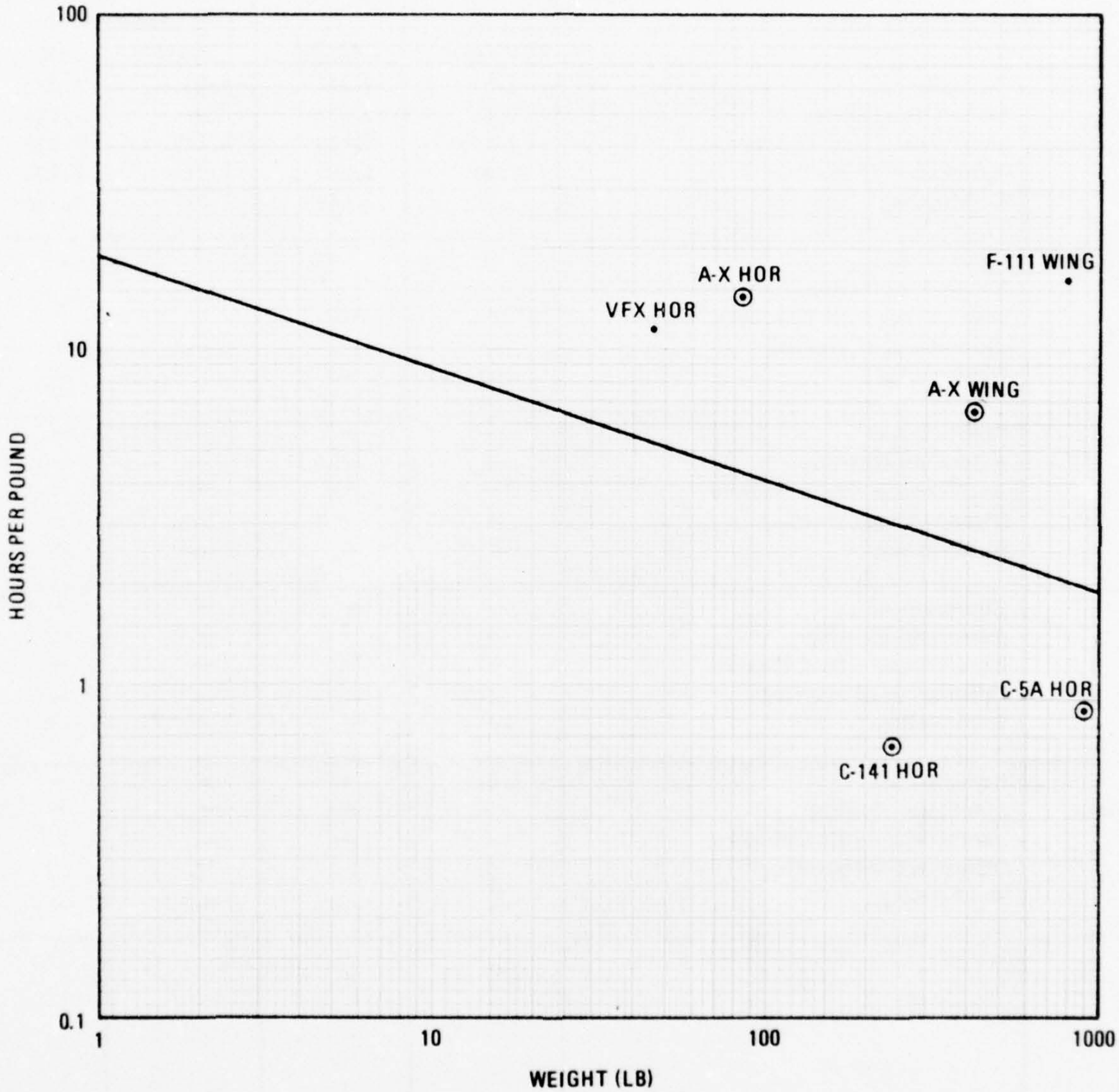


Figure 66. Spar Subassembly Hours Per Pound Against Weight

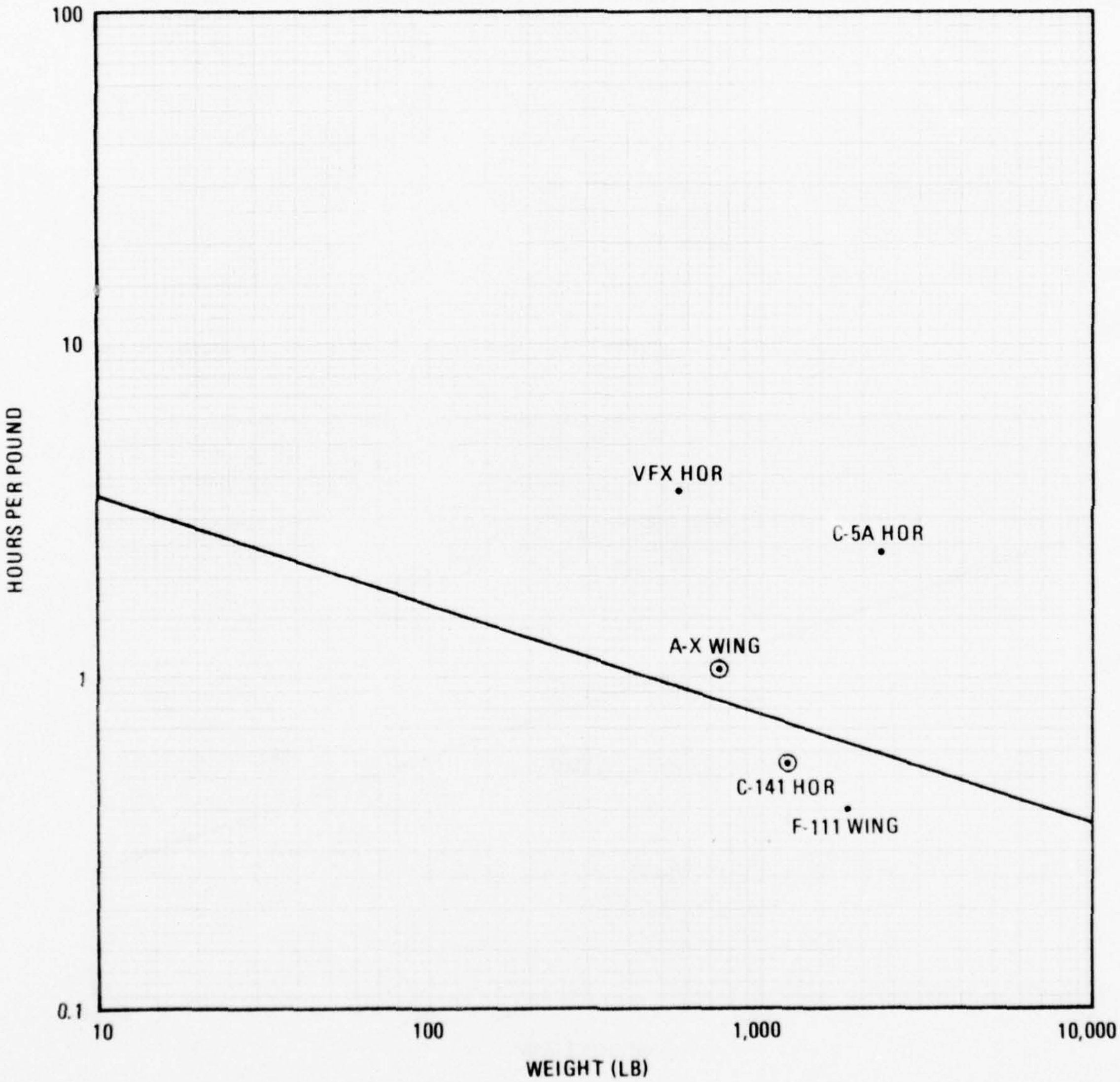


Figure 67. Cover Subassembly Hours Per Pound Against Weight

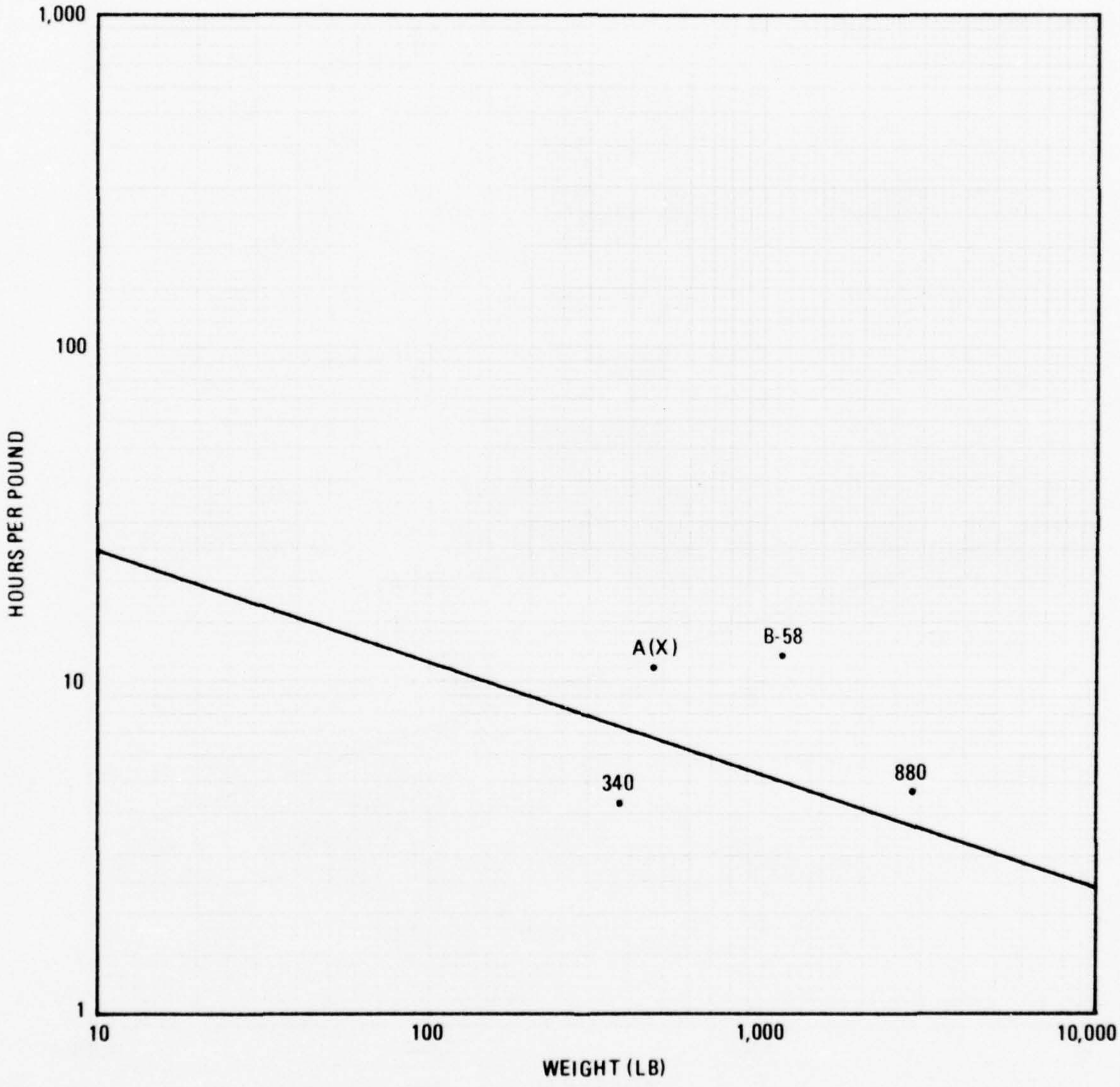


Figure 68. Frames Subassembly Hours Per Pound Against Weight

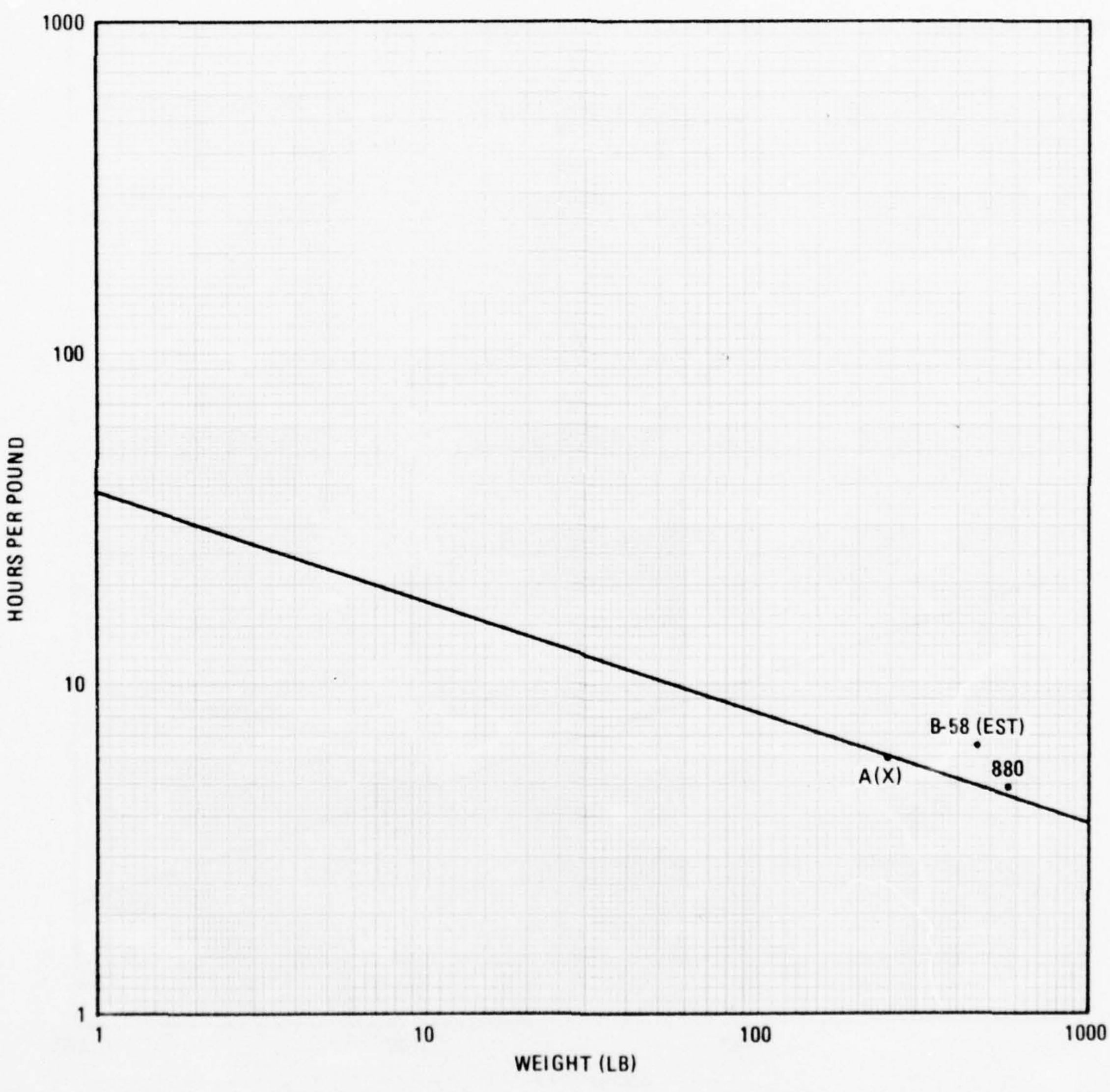


Figure 69. Longeron Subassembly Hours Per Pound Against Weight

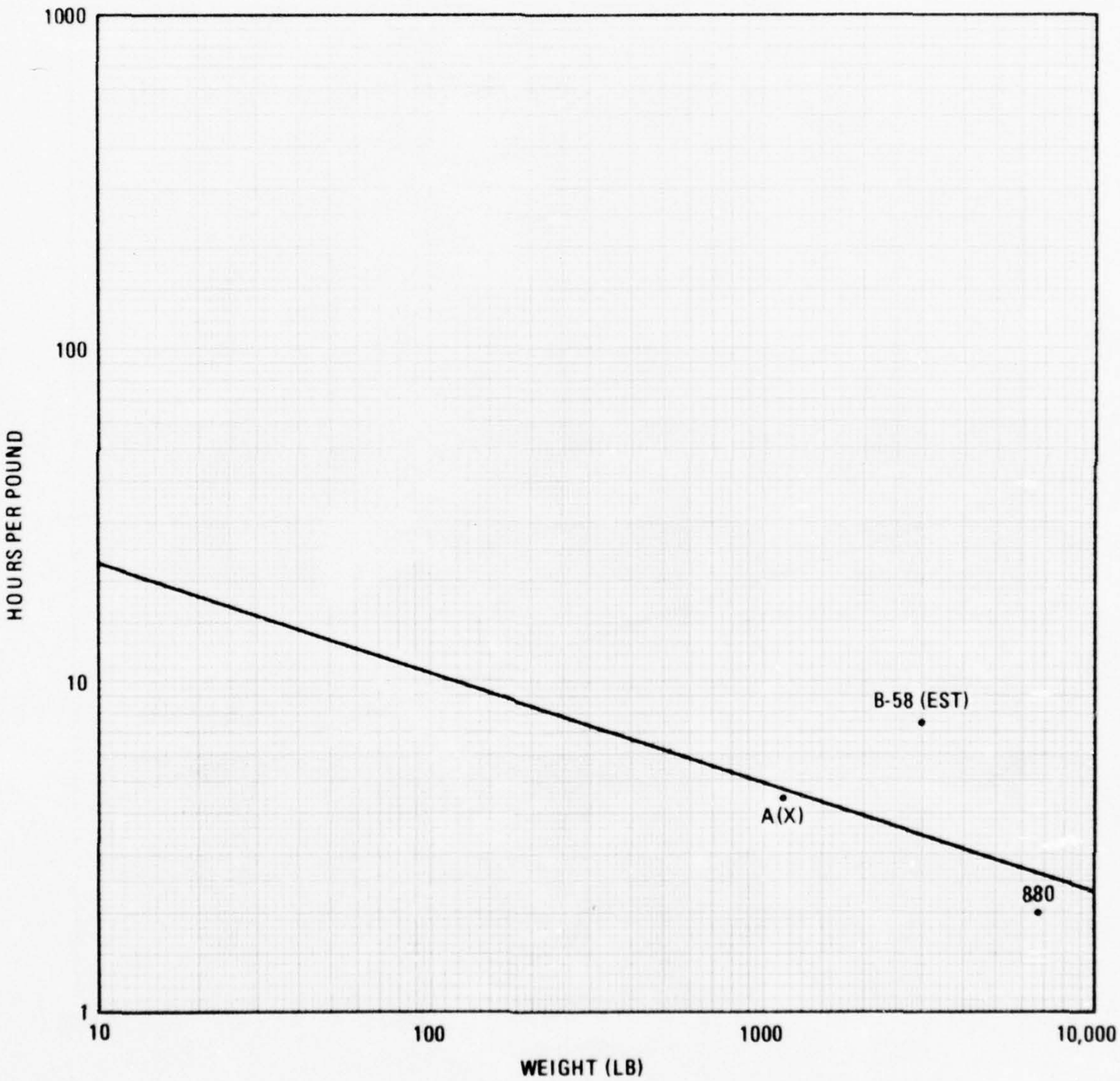


Figure 70. Skin Subassembly Hours Per Pound Against Weight

Table 37. Cost Per Pound Factors (HF_i) Map

SUBASSEMBLY LABOR	HF_i Code	Model Card Location	Model Card Value	Back-up Data Location
WING				
Rib	HF4	F 31 2	26.0	F-7
Spar	HF5	F 32 2	19.0	F-8
Cover	HF6	F 33 2	7.5	F-9
HORIZONTAL STABILIZER				
Rib	HF4	F 100 2	26.0	F-7
Spar	HF5	F 101 2	19.0	F-8
Cover	HF6	F 102 2	7.5	F-9
VERTICAL STABILIZER				
Rib	HF4	F 151 2	26.0	F-7
Spar	HF5	F 152 2	19.0	F-8
Cover	HF6	F 153 2	7.5	F-9
FUSELAGE				
Frames	HF4	F 201 2	52.0*	F-10
Longerons	HF5	F 202 2	38.0*	F-11
Skins	HF6	F 203 2	22.5**	F-12

*Factor of 2.0 on Aerodynamic Surfaces
**Factor of 3.0 on Aerodynamic Surfaces

These ratios are applied to the data developed for the complexity factor determination, as described in Reference 1, Appendix G, to arrive at modified factors. This was done as described below.

The starting point is the data developed by Industrial Engineering: the estimated cost of a representative structural element as illustrated in Figure 71 (Figure G-6 from Reference 1). The figure shows 4.0 hours required for subassembly of a built-up truss type of rib. This figure is adjusted by the ratios from Table 39 in the following manner:

Total subassembly	4.0 hours
Riveting	1.0 hours
Total less riveting	3.0 hours
Ratio from Table 39: (Ave.)	1.465 hours
Adjusted estimate for riveting	1.465 hours
Adjusted total	4.465 hours
Factor to be applied (4.465 ÷ 4)	1.116 hours

A factor is calculated for each of the rib, spar and cover sets of data contained in Appendix G of Reference 1. The resulting factors are entered in Tables 31 through 36. The factor calculated above is entered in Table 31 after being multiplied by the factor for the conventional approach for aluminum material. The materials identified in Tables 31 through 36 apply, of course, to the material being joined rather than the fastener material. The complexity of hole drilling in various metals is accounted for in the original set of factors in these tables.

Factors for automatic riveting were developed from data based on Ft. Worth manufacturing technology study (FMR 73-2250) examined the use of automatic riveting for lightweight fighter type structure and compared assembly costs to handriveting methods. Manual to automatic riveting recurring cost ratios, that were developed for generation of cost savings associated with specific aircraft production quantities, were identified and used as a partial data base for the development of automatic riveting complexity factors. The above manual to automatic riveting ratios were used in conjunction with additional Ft. Worth data developed at the subassembly level that compares handriveting with drivematic (automatic) riveting. The ratio of handriveted standard hours to drivematic standard hours was computed for each of the identified assemblies. These ratios were combined with those from FMR 73-2250 to yield a weighted average of the two data sources. The weighted automatic riveting average is approximately 5 to 1 as shown in Figure 72. This automatic riveting ratio was then used in a fashion similar to that for the interference fit fasteners. For each type of construction technique that requires riveting a factor was developed based on the percentage of subassembly attributed to

APPROVALS DATE

STATION SEQUENCE & LOAD CHART

LEGEND

BUILT-UP TRUSS
6

NOTES

STATION SUMMARY	1ST	2ND	3RD	TOTAL
STD. HRS.	7.2			
ACT. HRS.	23.5			
MANPOWER				

PROJECT
DEPT.
STATION
MOVE CYCLE
ASST. FOR
% REAL

Elap Hours 1 2 3 4 5 6 7 8 9 10 11 12 13 14

OPERATION NO / TITLE	ZONE	STD	ACT	CREW
Rib is a riveted truss assembly				
Detail parts are: cap rails (2) and extruded truss members (15) Clips (2)				
Cap rail fabrication				
Set-up Shear			.5	
Shear material to dim. 2" x 48" x .185"			.3	
Set-up router			.5	
Route scallops			.7	
Burr			.5	
Process per spec. (alodine)				
Identify and inspect.			.5	
Truss members (15)				
Set-up saw.			.5	
Saw extrusion to length			1.0	
Burr			.5	
Process to spec. (alodine)				
Prime surfaces			.7	
Identify and inspect.			.5	
Clip fabrication				
Set-up shear			.5	
Shear material to size 3" x 2" x .185"			.3	
Process to spec. (alodine)			4.0	
Prime surfaces			.2	
Identify and inspect.			.3	
Assembly of rib				
Load rails, clips and truss members in ASFX			.7	
Clamp (8)			.3	
Drill 64 3/16 holes in .185 material			1.0	
Cleco 20			.5	
Rivet 64 3/16 rivets			1.0	
Inspect			.5	
Forward to next assembly				
Total Detail Fab.			11.5	
Total Subassembly			4.0	

PERSONNEL

PREPARED BY

Figure 71. Built-Up Truss Rib Analysis

Manual/Automatic Recurring Cost Ratios*

Ratio	
7.29	Automatic Riveting**
3.35	
10.69	
$\bar{X}_1 = 7.11$	

Ratio	
1.18	Automatic Riveting Vs Sub-Assembly***
2.81	
4.16	
2.38	
2.29	
2.73	
3.34	
2.95	
3.55	
4.76	
4.53	
$\bar{X}_2 = 3.15$	

$$\frac{\bar{X}_1 + \bar{X}_2}{2} = \frac{3.15 + 7.11}{2} = 5.13$$

$$\approx 5$$

*Automatic Riveting capital investment is external to these ratios.

**Ft. Worth Manufacturing Technology FMR 73-2250 by W. R. King

***Ft. Worth Memo by M. O. Skinner

Figure 72. Automatic Riveting

riveting and the automatic riveting ratio. The calculations to develop these automatic riveting factors appear in Table 40. Each of these factors is based on aluminum and is developed independent of material type with the assumption being that the automatic versus handriveting costs are a function of the amount of riveting required to produce a given type of structure and not material type per se. As a second order effect the decision to use handriveting or automatic riveting on the basis of material type is a question that should be addressed with further research but is beyond the scope of current funding and the available data base. The above automatic riveting factors have been expanded to other material types based on the relative cost ratios associated with different materials where conventional riveting is used. Documentation of the above aluminum automatic riveting factors and ratioed other material automatic riveting factors appears in Tables 31 through 36. It is important to note that the automatic riveting factors developed in Table 40 have as a baseline the complexity factor for a given type of structure using conventional riveting and this factor isn't necessarily 1.0. The automatic riveting factors represent the percentage reduction in the complexity factor associated with a given type of construction (using conventional riveting) that is required to provide for automatic riveting.

Factors for diffusion bond riveting were developed in a similar fashion to those of automatic riveting and interference fit fasteners. The elemental ratio that controls the values of the diffusion bond riveting factor calculation matrix shown in Table 41 is the diffusion bond riveting ratio. The ratio of .6/1.0 was selected based on Convair performed manufacturing technology research (Reference 6). In this research report cost comparisons are made of various fastening techniques and diffusion bond riveting. Use of this ratio provides a basis for the development of diffusion bond riveting ratios that are similar in use to those factors developed for automatic riveting and interference fit fasteners. As before, the complexity factors developed for an aluminum construction are ratioed to provide for other types of material. Documentation of the above complexity factors appears in Tables 31 through 36.

Factors for weldbonding were developed in a similar way to the earlier factors. Manufacturing development research work was reviewed to provide a basis for a weldbonding ratio to specify the relative cost of fastening by weldbonding compared to conventional manual riveting. Table 42 summarizes and averages the ratios of weldbonding to handriveting costs that were recorded in the identified documents. The average value of the total sample ($\overline{X}_T = .80$) of weldbonding ratios was used to generate the weldbonding factors developed in Table 43. The factors shown at the bottom of the Table were then used in a similar fashion to those developed for automatic riveting, interference fit fasteners and diffusion bond riveting to develop complexity factors for weldbonding fastening. The developed complexity factors for weldbonding are summarized along with the other complexity factors in Tables 31 through 36.

Table 40. Automatic Riveting

	Ribs & Frames Built Up Web Stiffener	Ribs & Frames Built Up Truss	Spars & Longerons Built Up Web Stiffener	Spars & Longerons Built Up Truss	Covers & Skins Built Up Skin Stringer
Total Subassembly	4.5	4.0	3.1	3.7	5.5
Riveting	1.5	1.0	1.3	1.5	2.2
Total less riveting	3.0	3.0	1.8	2.2	3.3
Auto. Rivet Ratio	.2	.2	.2	.2	.2
Adj. Est. for Riveting	.3	.2	.26	.3	.44
Adjusted Total	3.3	3.2	2.06	2.5	3.74
Factor to be Applied	$\frac{3.3}{4.5} = .73$	$\frac{3.2}{4.0} = .8$	$\frac{2.06}{3.1} = .66$	$\frac{2.5}{3.7} = .67$	$\frac{3.74}{5.5} = .68$

Table 41. Diffusion Bond Riveting

	Ribs & Frames Built Up Web Stiffener	Ribs & Frames Built Up Truss	Spars & Longerons Built Up Web Stiffener	Spars & Longerons Built Up Truss	Covers & Skins Built Up Skin Stringer
Total Subassembly	4.5	4.0	3.1	3.7	5.5
Riveting	1.5	1.0	1.3	1.5	2.2
Total less Riveting	3.0	3.0	1.8	2.2	3.3
Diffusion Bond Riveting Ratio	.6	.6	.6	.6	.6
Adj. Est. for Riveting	.9	.6	.78	.9	1.32
Adjusted Total	3.9	3.6	2.58	3.1	4.62
Factor to be Applied	$\frac{3.9}{4.5} = .86$	$\frac{3.6}{4.0} = .9$	$\frac{2.58}{3.1} = .83$	$\frac{3.1}{3.7} = .83$	$\frac{4.62}{5.5} = .84$

Table 42. Weldbonding Cost Advantage Ratios

	Ratio*	Mean
Planning Memo, June 1973, Reference 7	.36	$\bar{X}_1 = .34$
	.32	
Weldbonding for Aerospace Structures Dec 1975, Reference 8	.62	$\bar{X}_2 = .90$
	.56	
	.89	
	.79	
	.85	
	.72	
	1.66	
	1.15	
	1.07	
	.74	
	$\bar{X}_T = .80$	

$$^{*}\text{Ratio} = \frac{\text{Weldbonding Cost}}{\text{Hand Riveting Cost}}$$

7. "Improvement of Titanium Weldbonding for High-Performance Aircraft Structures", Convair Memo RLS-491-0, June, 1973.

8. J. C. Gray and R. L. Szabo, "Weldbonding for Aerospace Structures", Convair Report CASD-ERR-75-039, December, 1975.

Table 43. Weldbonding

	Ribs & Frames Built Up Web Stiffener	Ribs & Frames Built Up Truss	Spars & Longerons Built Up Web Stiffener	Spars & Longerons Built Up Truss	Covers & Skins Built Up Skin Stringer
Total Subassembly	4.5	4.0	3.1	3.7	5.5
Riveting	1.5	1.0	1.3	1.5	2.2
Total less Riveting	3.0	3.0	1.8	2.2	3.3
Adhesive Bond Welding Ratio	.8	.8	.8	.8	.8
Adj. Est. for Riveting	1.2	.8	1.04	1.2	1.76
Adjusted Total	4.2	3.8	2.84	3.4	5.06
Factor to be Applied	$\frac{4.2}{4.5} = .93$	$\frac{3.8}{4.0} = .95$	$\frac{2.84}{3.1} = .91$	$\frac{3.4}{3.7} = .91$	$\frac{5.06}{5.5} = .92$

3.3.2.4 Equation Modifications. Major Assembly – Major assembly is that assembly required to join primary structure items after subassembly has been completed. It is the lowest level of assembly requiring assembly fixtures and operation and inspection log control. Its interface with the total manufacturing process is shown in Figure 73.

The decision to use automatic riveting in the major assembly process impacts the hole drilling estimating equation since automatic riveting provides for automatic drilling as well. The current hole drilling hours estimating equation for aero surfaces and fuselage can be modified by adding two terms, viz., AU (automatic riveting factor) and AP (automatic riveting percentage factor). The automatic riveting factor is a constant whose value is .2 and reflects the hole drilling advantages of conditions where all manual riveting could be done by automatic riveting equipment. Since any real riveting situation has some rivets that cannot be placed and formed by automatic equipment a second factor (AP) that identifies the percentage of total rivets that can be formed by automatic techniques is required. The factor takes values from .2 to 1.0 depending on the percentage of total riveting that can be accomplished by automatic means. Table 44 shows the values of AP that are appropriate for various percentages of rivets that can be accomplished by automatic means.

The modified equation for aero surface and fuselage hole drilling that now provides for automatic riveting is as follows:

$$H_i = 2\left[(RP)^R (RN)^Q + (SPE)^R (SNE + SNI)^Q\right]$$

$$(HD)\ (TJ4)\left(\frac{AU}{AP}\right) \text{ (Modified Equation No. 7*)}$$

The decision to use automatic riveting or interference fit fasteners in the major assembly process impacts the fastener installation estimating relationship in a similar fashion to that for hole drilling. As above for automatic riveting hole drilling the factors AU/AP must be added with identical values to those above. For interference fit fasteners the factors IF/IP must be added with IF having a constant value of 1.5 and IP taking on values of 1.5 to 1.0 depending on the percentage of total fasteners that are interference fit fasteners. Table 45 shows the values of IP that are appropriate for various percentages of fasteners that are interference fit. The modified equation for fastener installation for aero surface and fuselage that now provides for automatic riveting or interference fit fasteners is as follows:

$$H_i = 2\left[(RP)^R (RN)^Q + (SPE)^R (SNE + SNI)^Q\right]$$

$$(HFI)\ (TJ4)\ (FF2)\left(\frac{IF^{**}}{IP}\right) \text{ (Modified Equation No. 9*)}$$

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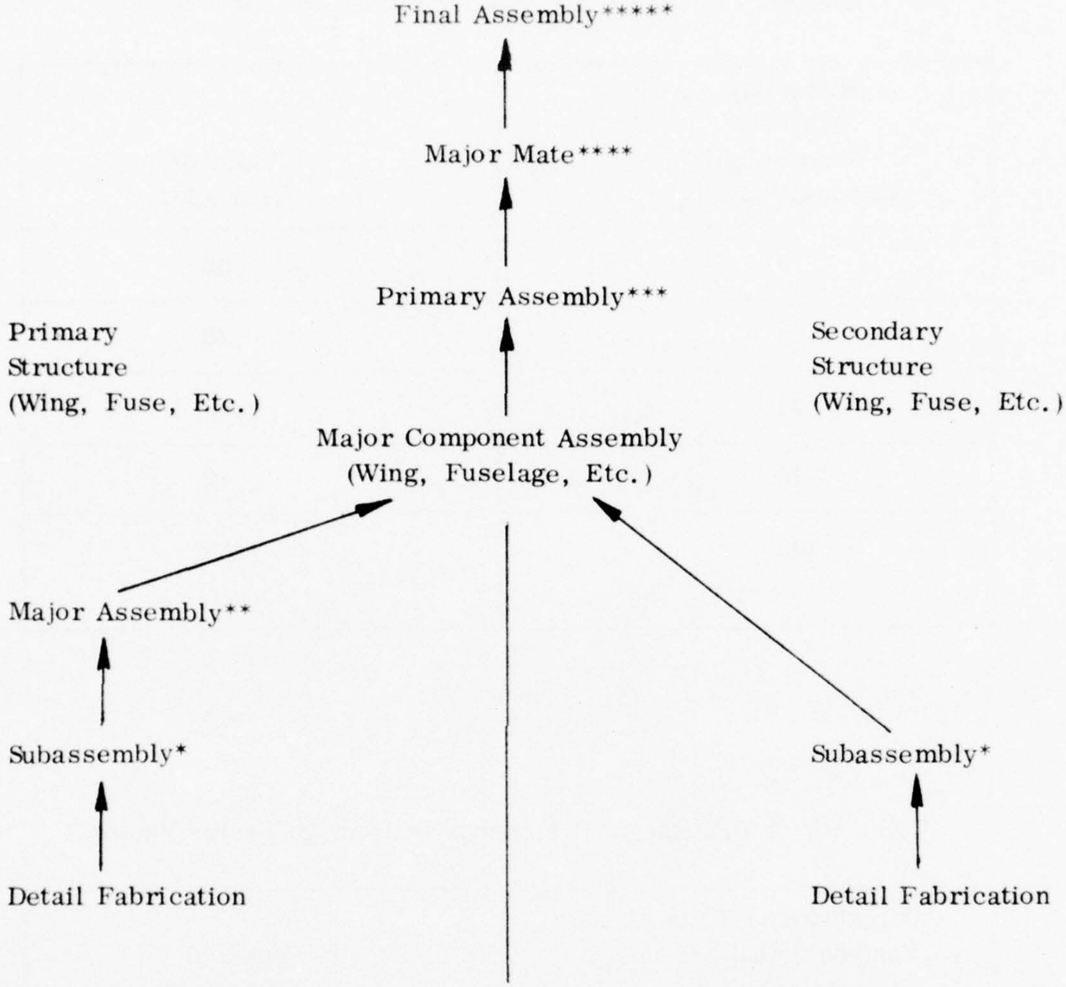
*AFFDL-TR-75-44, Vol. II, Part 1, May 1975 (Reference 1)

**Or $\frac{AU}{AP}$ for automatic riveting



*Bench assembly not requiring assembly fixtures.

**Lowest level assembly requiring assembly fixtures and operation and inspection log (OIL) control.

***Installation, assembly and checkout of functional subsystems.

****Joining together of major structural components (wing, fuselage, etc.).

*****Highest level assembly where engines and avionics are added.

Figure 73. Manufacturing Interface Diagram

Table 44. Automatic Riveting Percentage Factor Values

Percentage of rivets formed by automatic means	Value of AP Factor
0	.20
25	.40
50	.60
75	.80
100	1.00

Table 45. Interference Fit Fastener Percentage Factor Values

Percentage of Total Fasteners that are Interference Fit	Value of IP Factor
0	1.5
25	1.375
50	1.25
75	1.125
100	1.0

3.4 EVALUATION OF COMMONALITY

Commonality refers to the degree to which a piece of structure or other system is composed of similar or identical parts. High commonality implies a high degree of part similarity and low commonality a low degree of part similarity. The following sections develop a cost methodology for the determination of the recurring production cost impacts of varying degrees of commonality and a discussion of the production run set up cost impacts of commonality.

3.4.1 COMMONALITY EFFECTS ON RECURRING PRODUCTION COSTS. The production cost benefits of commonality can be conveniently categorized into recurring and non-recurring cost. The non-recurring cost benefits accrue from reduced production set up costs since the production of identical parts requires only one set-up rather than many. The recurring cost benefits accrue from reduced unit costs that are the result of greater learning on longer production runs. Idealy, it would be desirable to identify each structural part that is produced in quantity and account for the commonality cost benefits associated with producing identical parts rather than distinctly different ones. Practical modeling and funding constraints, however, dictate that a more generalized approach be used. Such a generalized approach has been developed by examining the boundary conditions of a given piece of structure, i.e., the case where there is no commonality of parts and the case where there is complete commonality of parts. Formulation of mathematical expressions for these boundary sets of conditions can then be combined to provide a formulation for the generalized condition of a mix of common and uncommon parts. For the condition where there are no common parts, learning can be accounted for at the aggregate level by the following expression:

$$a\,(SS)^{b}$$

where

a = first unit cost of aggregate structure
ss = number of shipsets of aggregate structure
b = learning factor

For the condition where there are no uncommon parts in an aggregate piece of structure (e.g., the case of all the ribs in a constant cord airfoil) learning can be accounted for by the following expression:

$$\frac{a}{NCP} \times (SS \text{ X } NCP)^{b}$$

where

a = first unit cost of aggregate structure
NCP = number of common parts
b = learning factor

To deal with the more common case where there is a mixture of common parts and uncommon parts a composite equation that represents a weighted distribution of the contribution of the common and uncommon parts to the total cost is used. This equation is shown below and requires the additional variable of p; which is a measure of the percentage of aggregate structure that is composed of common parts. The specific equation is as follows:

(Equation a)

$$\text{Cost} = (1 - p)\ a\ (SS)^{b} + \frac{p\ (a)}{NCP}\left[SS\ (NCP)\right]^{b}$$

where

a = first unit cost of aggregate structure
NCP = number of common parts
SS = number of shipsets of aggregate structure
b = learning factor
p = percentage of parts that are common by part count

For the primary structure, consisting of ribs, spars, covers, frames and longerons specific equations based on Equation a above have been developed for both detail fabrication and subassembly. A tabulation that identifies the proper equation to be used with each piece of primary structure appears for detail fabrication and subassem as Table 46 and Table 47. The letter identified with each piece of primary structure refers to the equations, A thru J, shown in Figure 73. The letter identified with each piece of secondary structure refers to the general secondary structural equation form shown below;

Equation K:

$$\begin{array}{l}\text{Secondary Structure} \\ \text{Item cost}\end{array} = (1-p)\ TFU\ (SS)^{b} + \frac{p\ (TFU)}{NCP}\left[SS(NCP)\right]^{b}$$

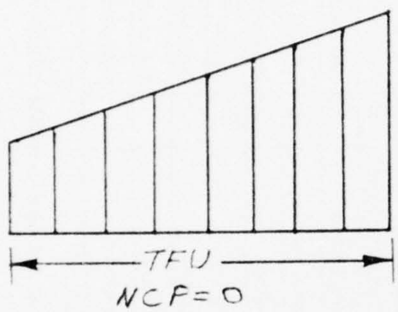
where

p = percentage of secondary structure item that has common parts *
TFU = Theoretical First Unit cost of secondary structure item
SS = Number of shipsets
NCP = Number of common parts
b = learning factor

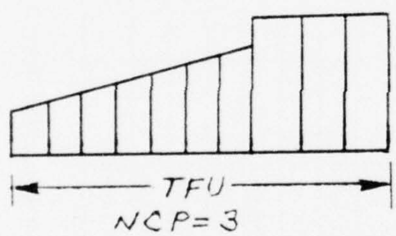
* Determined by part count; or cost, if available.

A simplified graphic presentation of the proper determination of the number of common parts (NCP) for the three possible conditions of complete, partial and no commonality appears below;

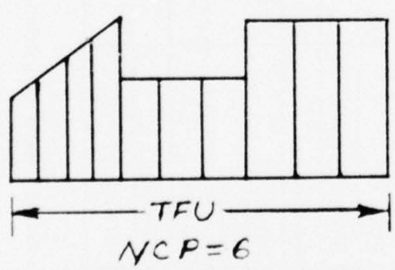
NCP DETERMINATION



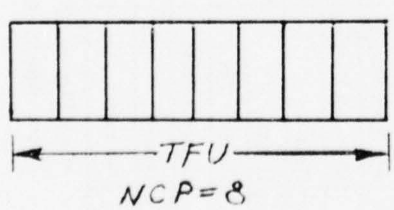
Fin (None)



Engine Provisions (Partial)



Leading Edge (Partial)



Balance Weights (Complete)

Table 46. Commonality Equations* for Detail Fabrication of Primary and Secondary Structure

Symbol	Wing		Horizontal		Vertical		Fuselage		Nacelle		Landing Gear	
PC11	Ribs	A	Ribs	A	Ribs	A	Frames	D	Not used		Not used	
PC12	Spars	B	Spars	B	Spars	B	Longerons	E	Not used		Not used	
PC13	Covers	C	Covers	C	Covers	C	Covers	C	Not used		Not used	
PC14	Not used		Not used		Not used		Not used		Not used		Not used	
PC15	Leading Edge	K	Leading Edge	K	Leading Edge	K	Cockpit	K	Cowling	K	Brakes	K
PC16	Trailing Edge	K	Trailing Edge	K	Trailing Edge	K	Nose LG Door	K	Pylon	K	Brake Cont.	K
PC17	Ailerons	K	Fairings	K	Fairings	K	Wing Box	K	Main LG Door	K	Wheels	K
PC18	Fairings	K	Tips	K	Tips	K	Tail Attachment	K	Not used		Tires	K
PC19	Tips	K	Attach Structure	K	Attach Structure	K	Windshield	K	Not used		Oleos	K
PC110	Spoilers	K	Access	K	Access	K	Main LG Door	K	Not used		Axles	K
PC111	Flaps	K	Hinges	K	Hinges	K	Fuel Provisions	K	Not used		Drag Braces	K
PC112	Attach Structure	K	Pivots	K	Rudder	K	Engine Provisions	K	Not used		Not used	
PC113	Access Doors	K	Center Section	K	Not used		Duct Provisions	K	Not used		Not used	
PC114	Air Induction	K	Elevators	K	Not used		Stores Provisions	K	Not used		Not used	
PC115	High-Lift Ducting	K	Balance Weights	K	Not used		Speed Brakes	K	Not used		Not used	
PC116	Slats	K	Not used		Not used		Cabin Flooring	K	Not used		Not used	
PC117	Hinges	K	Not used		Not used		Windows	K	Not used		Not used	
PC118	Pivots & Folds	K	Not used		Not used		Doors	K	Not used		Not used	
PC119	Center Section	K	Not used		Not used		Not used		Not used		Not used	
PC120	Other	K	Not used		Not used		Not used		Not used		Not used	
PC121	Not used		Not used		Not used		Not used		Not used		Not used	

*See Figure 73

Note: Above equations are used to account for recurring (learning curve) cost benefits of commonality

Table 47. Commonality Equations* for Subassembly of Primary and Secondary Structure

Symbol	Wing		Horizontal		Vertical		Fuselage		Nacelle		Landing Gear	
PC11	Ribs	F	Ribs	F	Ribs	F	Frames	I	Not used		Not used	
PC12	Spars	G	Spars	G	Spars	G	Longerons	J	Not used		Not used	
PC13	Covers	H	Covers	H	Covers	H	Covers	H	Not used		Not used	
PC14	Not used		Not used		Not used		Not used		Not used		Not used	
PC15	Leading Edge	K	Leading Edge	K	Leading Edge	K	Cockpit	K	Cowling	K	Brakes	K
PC16	Trailing Edge	K	Trailing Edge	K	Trailing Edge	K	Nose LG Door	K	Pylon	K	Brake Cont.	K
PC17	Ailerons	K	Fairings	K	Fairings	K	Wing Box	K	Main LG Door	K	Wheels	K
PC18	Fairings	K	Tips	K	Tips	K	Tail Attachment	K	Not used		Tires	K
PC19	Tips	K	Attach Structure	K	Attach Structure	K	Windshield	K	Not used		Oleos	K
PC110	Spoilers	K	Access	K	Access	K	Main LG Door	K	Not used		Axles	K
PC111	Flaps	K	Hinges	K	Hinges	K	Fuel Provisions	K	Not used		Drag Braces	K
PC112	Attach Structure	K	Pivots	K	Rudder	K	Engine Provisions	K	Not used		Not used	
PC113	Access Doors	K	Center Section	K	Not used		Duct Provisions	K	Not used		Not used	
PC114	Air Induction	K	Elevators	K	Not used		Stores Provisions	K	Not used		Not used	
PC115	High-Lift Ducting	K	Balance Weights	K	Not used		Speed Brakes	K	Not used		Not used	
PC116	Slats	K	Not used		Not used		Cabin Flooring	K	Not used		Not used	
PC117	Hinges	K	Not used		Not used		Windows	K	Not used		Not used	
PC118	Pivots & Folds	K	Not used		Not used		Doors	K	Not used		Not used	
PC119	Center Section	K	Not used		Not used		Not used		Not used		Not used	
PC120	Other	K	Not used		Not used		Not used		Not used		Not used	
PC121	Not used		Not used		Not used		Not used		Not used		Not used	

*See Figure 73

Note: Above equations are used to account for recurring (learning curve) cost benefits of commonality

Equation A:

$$\text{Ribs Cost} = (1-P_r)\, R_D\, (SS)^{b} + \frac{Pr\,(R_D)}{NCR}\left[SS\,(NCR)\right]^{b}$$
(Total Procurement)

where

Pr = percentage of ribs that are common by part count. **
R_D = Detail fabrication cost of ribs in total * without commonality
SS = Number of shipsets
NCR = Number of common ribs
b = Learning factor

Equation B:

$$\text{Spars Cost} = (1-Ps)\, S_D\, (SS)^{b} + \frac{Ps\,(S_D)}{NCS}\left[SS\,(NCS)\right]^{b}$$
(Total Procurement)

where

Ps = percentage of spars that are common by part count. **
S_D = Detail fabrication cost of spars in total * without commonality
SS = Number of shipsets
NCS = Number of common spars
b = learning factor

Equation C:

$$\text{Covers Cost} = (1-Pc)\, C_D\, (SS)^{b} + \frac{Pc\,(C_D)}{NCC}\left[SS\,(NCC)\right]^{b}$$
(Total Procurement)

where

Pc = percentage of covers that are common by part count. **
C_D = Detail fabrication cost of covers in total * without commonality
SS = Number of shipsets
NCC = Number of common covers
b = learning factor

* Complete shipset
** Or by cost; if available

Figure 74. Commonality Equations

Equation D:

$$\text{Frames Cost} = (1\text{-Pf})\ F_D\ (SS)^{b} + \frac{Pf\ (F_D)}{NCF}\left[SS\ (NCF)\right]^{b}$$

(Total Procurement)

where Pf = Percentage of frames that are common by part count. **
F_D = Detail fabrication cost of frames in total * without commonality
SS = Number of shipsets
NCF = Number of common frames
b = learning factor

Equation E:

$$\text{Longerons Cost} = (1-P_L)\ L_D\ (SS)^{b} + \frac{P_L\ (L_D)}{NCL}\left[SS\ (NCL)\right]^{b}$$

(Total Procurement)

where P_L = Percentage of frames that are common by part count. **
L_D = Detail fabrication cost of longerons in total * without commonality
SS = Number of shipsets
NCL = Number of common longerons
b = Learning factor

Equation F:

$$\text{Ribs Cost} = (1\text{-Pr})\ Rs\ (SS)^{b} + \frac{Pr\ (Rs)}{NCR}\left[SS\ (NCR)\right]^{b}$$

(Total Procurement)

where Pr = Percentage of ribs that are common by part count **
Rs = Subassembly cost of ribs in total * without commonality
SS = Number of shipsets
NCR = Number of common ribs
b = Learning factor

* Complete shipset
** Or by cost; if available

Figure 74. Commonality Equations (continued)

Equation G:

$$\text{Spars Cost} = (1 - Ps)\ S s\ (SS)^{b} + \frac{Ps\ (Ss)}{NCS} \left[SS\ (NCS) \right]^{b}$$

(Total Procurement)

where
Ps = Percentage of spars that are common by part count **
Ss = Subassembly cost of spars in total * without commonality
SS = Number of shipsets
NCS = Number of common spars
b = Learning factor

Equation H:

$$\text{Covers Cost} = (1 - Pc)\ Cs\ (SS)^{b} + \frac{Pc\ (Cs)}{NCC} \left[SS\ (NCC) \right]^{b}$$

(Total Procurement)

where
Pc = Percentage of covers that are common by part count **
Cs = Subassembly cost of covers in total * without commonality
SS = Number of shipsets
NCC = Number of common covers
b = Learning factor

Equation I:

$$\text{Frames Cost} = (1 - Pf)\ Fs\ (SS)^{b} + \frac{Pf\ (Fs)}{NCF} \left[SS\ (NCF) \right]^{b}$$

(Total Procurement)

where
Pf = Percentage of frames that are common by part count **
Fs = Subassembly cost of frames in total * without commonality
SS = Number of shipsets
NCF = Number of common frames
b = Learning factor

* Complete shipset
** Or by cost; if available

Figure 74. Commonality Equations (continued)

Equation J:

$$\text{Longerons Cost} = (1-P_L)\ Ls\ (SS)^{b} + \frac{P_L\ (Ls)}{NCL}\left[SS\ (NCL)\right]^{b}$$

(Total Procurement)

where P_L = Percentage of frames that are common by part count. **
Ls = Subassembly cost of longerons in total * without commonality
SS = Number of shipsets
NCL = Number of common longerons
b = learning factor

* Complete shipset
** Or by cost; if available

Figure 74. Commonality Equations (continued)

3.4.2 COMMONALITY EFFECTS ON SET UP COSTS. Set up costs are those costs accrued in setting up or preparing machines as a preliminary to actually producing a part. Set up costs specifically refer to the detail fabrication activities of a machine shop or numerically controlled production facility. Set up costs are distinguished from run time costs which accure when a piece or part is actually being produced.

In general, set up costs can be considered a distinct cost element whose magnitude is greatly dependent on the type and complexity of the part to be produced. If the production run of a particular part is long, the contribution of set up cost per part is small due to cost spreading. If the production run of a particular part is short the contribution of set up cost per part can be large. In quantitative terms, for an average piece of machined structure, the set up time would be approximately 200 - 250% of the theoretical first unit run time. Assuming a production run of 25 units, set up time w ould reduce to 8 - 10% of production unit run time, neglecting for the moment learning effects. From the above, it can be seen that the importance of set up costs is a direct function of the quantity of parts produced by a given setup. To the extent that commonality effects the quantity of parts produced by a given setup, commonality can effect the contribution of set up costs to total production costs. For purposes of analysis it is useful and valid to consider set up cost as a distinct element of cost that can be expressed as a percentage of theoretical first unit cost that is independent of considerations of commonality per se. With high part commonality this set up cost would be incurred less frequently than would be the case with low commonality. For an average piece of machined structure if only one piece were produced the set up costs as a percentage of total production costs would be significant (200 - 250% of the theoretical first unit labor cost). Even with an assumption of no commonality, a reasonable lot size of 25 shipsets

would reduce setup costs to less than 10% of total production labor cost. Assuming commonality that involved the use of 10 similar parts per ship set reduces set up costs to less than 1% of total production labor cost. Since aircraft production could easily involve lot sizes of 25 and some degree of commonality would be present the effect of changes in commonality on set up costs as a percentage of production costs become relatively insignificant. This fact coupled with the fact that the current cost model has set up costs buried in unit production cost (thereby making set up costs difficult to identify and isolate) leads to the decision to not provide a modification to the existing program to provide for set up cost sensitivity to changes in degree of commonality. In addition, the task of modeling the complete effects and sensitivities of set up costs is a complex one appropriate to the production level rather than the design level. Set up costs are a complex phenomenon that involves consideration of hardware design, specific machine capabilities, lot sizes, factory layout and schedule requirements and as such should be part of a detailed factory production plan but not a design trade study cost model such as the current one.

3.5 PRODUCTION RATE EFFECTS

Production rate effects refer to those cost impacts associated with changes in the rate at which an element or complete aerospace vehicle is produced. This research effort deals first with a review of the pertinent literature in Section 3.5.1 and then the analysis and development of cost estimating relationships to quantitatively assess the impacts of production rate effect in Section 3.5.2.

3.5.1 LITERATURE REVIEW – A literature search for published and unpublished material associated with production rate effects on hardware production costs was made. A reasonable selection of source documents was assemblied that includes the open literature of research institutes, private publishing houses, internal General Dynamics - Convair documents and unpublished papers. A careful reading of the above sources reveals that the subject of production rate effects is a subtle one where semantic ambiguity often results in conceptual confusion. For instance, the otherwise excellent study: Implications of Production Rate on Manufacturing Costs (Reference 9) fails to clearly distinguish production rate effects from learning effects. Imprecise understanding of the theory of learning curves results in the erroneous comingling of learning effects and rate effects. It is important to distinguish volume from rate. The clearest exposition of the relationship of production rate effects to learning can be found in: Analysis of Direct Labor Costs for Production Program Stretchouts (Reference 10). Learning effects are properly ascribed to the benefits of producing large quantities of an item (volume) and not the relative benefits of producing them rapidly or slowly (rate). The combined effects of learning and production can be described by a curved trough shape with the learning curve describing the long axis curve, as shown in Figure 75.

As shown here, the rate effects are really a second order phenomena. Production rate effects really are the result of using a given production facility in an optimum way or something less than that. A specific production facility has a production rate (usually close to the production rate that it was designed for) that provides an optimum mix of input/output (Reference 11). Deviations from this optimum (either by under-capacity or overcapacity) results in increased unit production costs. In essence, the task is to optimize the production process; not maximize it. The goal is to provide an optimum, smooth flow of a product from a production facility. From a rate effects point of view, there isn't necessarily an advantage to producing a large quantity of an item in a short period of time. In general, the benefit of producing large quantities of an item in a short period of time accrues from the spreading out of overhead or burden items over a large production quantity and not the benefit of producing at an optimum rate per se. It is important to note that attempting to produce too large a quantity of an item in a short period of time results in diminishing returns. The benefits of overhead spreading are outweighted by the diseconomy of forcing inordinately large production quantities through a given production facility. Once again, the goal is to increase production to a level that optimizes the spreading of overhead and utilization of production facility rather than maximization per se.

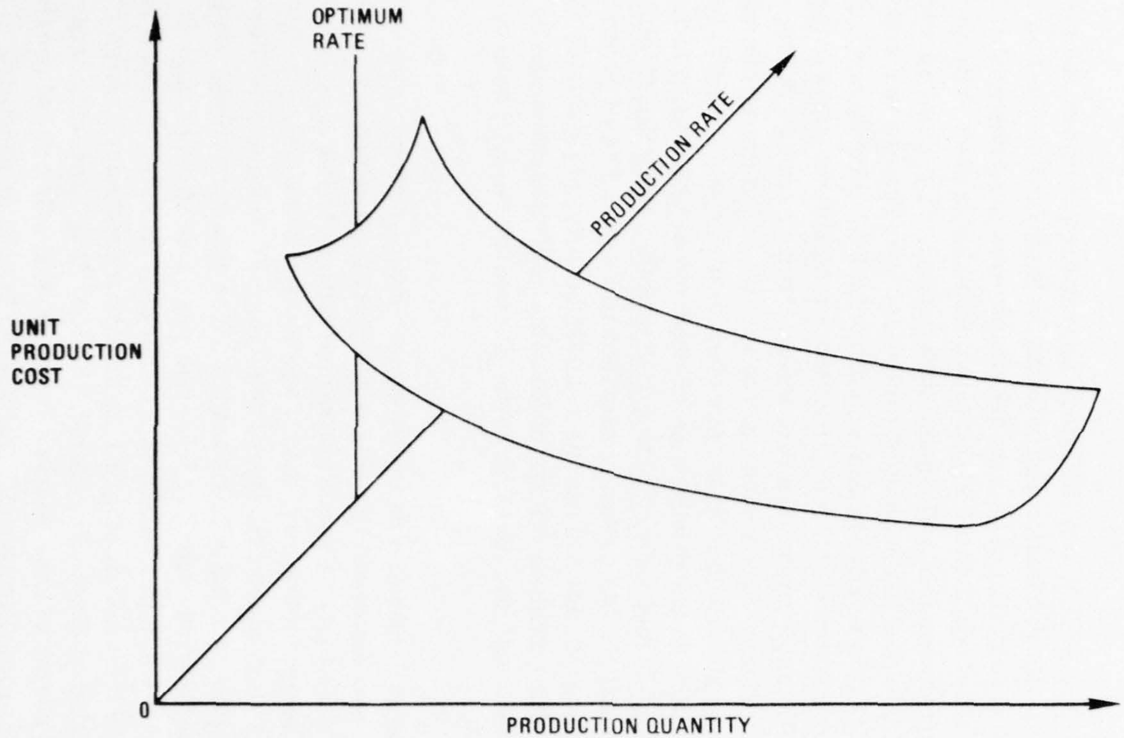


Figure 75. Volume/Rate Surface

A separate issue, but increasingly important based on recent experience, is the problem of inflation. In an economy with a high rate of inflation it becomes a real possibility that something can be produced significantly cheaper now than in the future. To the extent that rate effect determines when a specific flight article is built, inflation can be a significant variable in any rate effects discussion. The relationship of rate effects to inflation, however, is beyond the scope and funding of this current effort and will be excluded from further analysis and discussion. In that sense, the effects of production rate on production cost will be dealt with as a separate and distinct economic phenomena independent of the larger societal economic conditions.

3.5.2 COST ESTIMATING RELATIONSHIP (CER) MODIFICATION – In developing a methodology that systematically and quantitatively establishes the effect of different rates of production, basic definitions and levels of analysis must be identified and related to establish a relatively unambiguous basis for analysis and methodology development. Clear definitions and understanding of the phenomena to be analyzed and quantified leads to reduced degrees of freedom and potential misinterpretation of empirical data. Cost phenomena are inherently imprecise and attempts to eliminate as much ambiguity as possible in the data base, by systematic analysis, proves to be time well spent.

As discussed above, in the section on the literature review, production rate effects are a separate and distinctly different phenomenon from learning effects. Both effects can result in reduced or increased unit production costs but their causal basis is quite different. Production rate effects affect cost by consideration of how rapidly an item is produced. Learning effects, on the other hand, affect cost by consideration of how much of an item is produced. Production rate effects are concerned with the optimum flow and utilization of inputs required to produce a given piece of hardware. Learning effects are concerned with the act of knowing how to do something better (and hence less expensively) because you have done it before. The combined effects of both of the above phenomenon can be erroneously lumped together but doing so obscures and complicates two simpler processes.

To clearly define the production rate effect in isolation from learning effects the following flow chart (Figure 76) identifies the relevant variables and their relationship to one another. The production process can be thought of as requiring the inputs of people, materials, money, machines and plant over a given time period to produce, in this case, aircraft airframes at some monthly rate. Attempting to produce aircraft airframes at different monthly rates requires varying commitments of people, materials, money, machines and plant. The five items on the left in Figure 76 can be considered cost segments or drivers in any determination of the cost impacts of varying production rates. Some of the cost segments are sensitive to changes in the

production rate and some are not. It is the composite of these individual cost segments that determines the effect of production rate on unit production cost. Figure 77 identifies the production rate sensitivity of each of the cost elements showing that a given production rate has a unique production cost sensitivity dependent on the specific mix of the component cost segments and their individual sensitivity to changes in production rate.

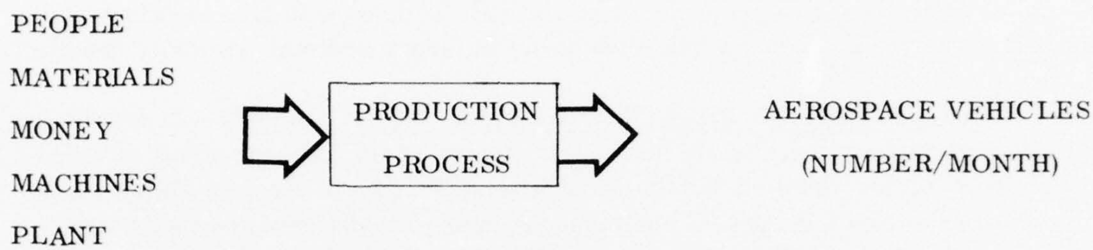


Figure 76. Production Process

Attempts were made to isolate and identify production rate cost sensitivities at the cost segment level with the intent of determining a composite production rate sensitivity curve that was a summation of the lower level curves. This approach appears to be feasible and would provide an excellent theoretical basis for the production rate effects phenomenon with visibility into lower level relationships. Unfortunately, the level of funding of this current study precludes further exploration of this approach due to the need to generate a basically new structuring of historical cost data. The less desirable, though acceptable, approach of examining empirical data at an aggregate unit production cost level was chosen as a viable alternative. This approach necessarily results in less understanding of the phenomenon in question; but in light of the time and funding constraints it will be used.

Cost Segment		Production Rate Sensitive	Not Production Rate Sensitive***
A	People Cost	√*	
B	Materials Cost	√*	
C	Money Cost		√**
D	Machinery Cost		√*
E	Facility Cost		√**

*Principally Variable Cost
**Principally Fixed Cost
***In the Short Term

Figure 77. Production Rate Sensitivities

To adequately examine and analyze empirical data on production rate effects it is important to have some theoretical understanding of the major parameters and considerations. An excellent treatment of the basic concepts can be found in Reference 7, Chapter 10. This basic treatment is concerned with long term and short term optimization of a production facility; but the basic concept of bucket shaped curves that are sensitive to production rate have direct application in interpreting empirical data. An appreciation of the theoretical foundations of an empirically observed phenomenon results in sounder interpretation of data and more meaningful mathematical constructs.

Figure 78 is a graphical presentation of historical empirical constructs and experience with variations in production rate. In general terms, they represent differing opinions and experience with reduced production rates. The most recent transport aircraft experience is represented by Curve C. Curve B represents an empirical curve derived by Vail (Reference 12). Support for the almost straight line relationship of Curve C, which represents recent production line experience can be found in the preface to Reference (13).In this reference Kelley makes the, apparently commonly experienced, observation that straight line relationships rather than more complex mathematical relationships are good estimators of relatively complex social science phenomenon. The combined virtues of most recent experience, real world production experience, mathematical simplicity and apparent theoretical/empirical support á la Kelley leads to the selection of a straight line relationship for incorporation into the existing cost methodology developed under Contract F33615-72-C-2083. The relationship to be used is as follows:

$$\text{Unit Production Cost Ratio} = \frac{\text{Unit Production Cost (Actual Rate)}}{\text{Unit Production Cost (Ideal Rate)}} = 1.16 - .16R$$

where

$$R = \frac{\text{Actual Rate}}{\text{Ideal Rate}}$$

within $.5 \leq R \geq 1.4$

Excursions beyond the specified range should not be made since dramatic variations are theoretically possible due to high slope production facility constraints that can become operative (Reference 7).

The above relationship allows a quantitative assessment of the cost impact of operating a production facility at a rate other than that for which the original production line was designed. With a completely new product and/or production facility there would not be a rate effect since the production line could be optimized for the prevailing set of conditions. When exercising the model, the specific set of conditions for actual rate and ideal rate in the determination of R should be used. In the absence of specific data for a particular model run, the value of R should be set to 1.0.

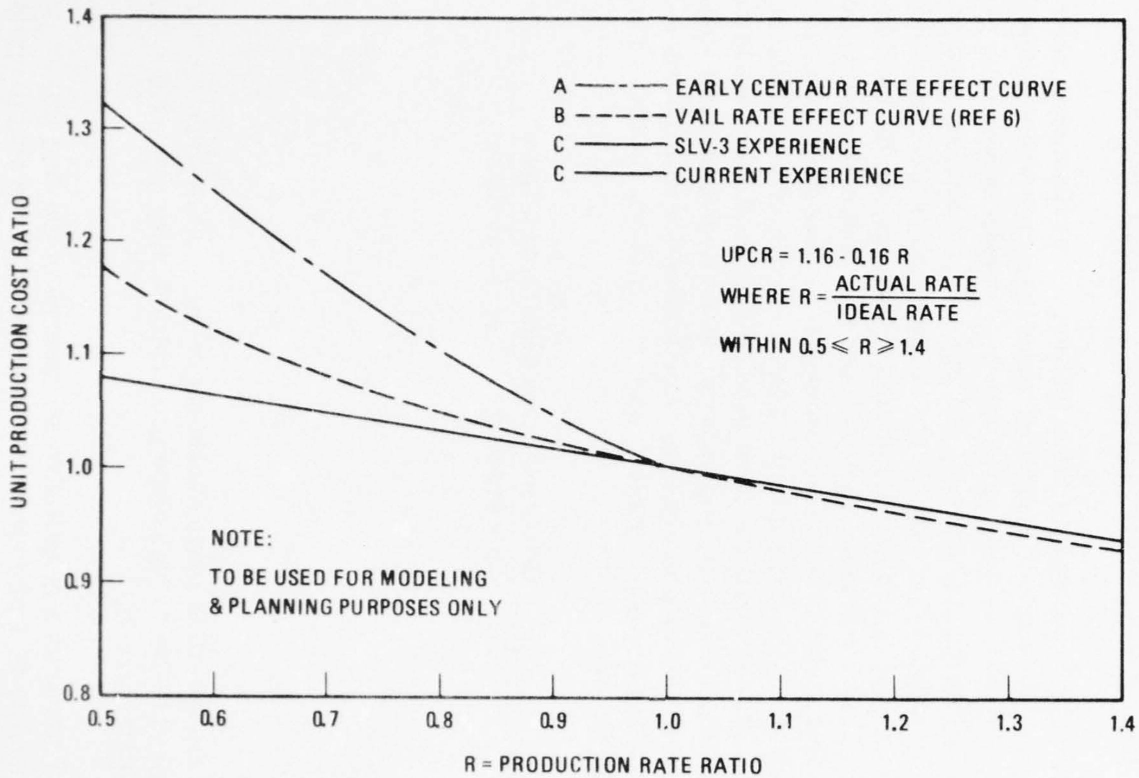


Figure 78. Rate Effects Curves

3.6 LEARNING CURVE FACTORS

Learning curve factors are those values associated with the amount of learning achieved in the production of a given piece of hardware. The following sections develop a subsystem level framework and set of learning factors for the determination of overall learning for a specific piece of structure.

3.6.1 LEARNING CURVES. A specific piece of aircraft structure represents a unique mix of machined parts, sheet metal parts, composite structure, and assembly. This unique mix of structural elements and tasks establishes a specific learning that is associated with that piece of aircraft structure. To model production learning and adequately reflect the specifics of a given piece of aircraft structure, it is necessary to develop learning curves at a lower level than the aggregate piece of structure. By identification of the percentage distribution of various types of structural elements within a given piece of structure, a weighted learning factor that reflects that specific structure can be obtained. Based on discussions with production estimating people, review of manufacturing engineering literature and personal knowledge of production and manufacturing processes; four different elements of production activity were developed. The detail fabrication portion of production is segmented into sheet metal fabrication, composite structure production, machine shop activity and numerically controlled production processes. Subassembly, which combines and joins parts produced in detail fabrication, is segmented into categories that parallel those of detail fabrication with the exception of numerically controlled machining where subassembly is not applicable. The learning rates for detail fabrication of high, medium and low learning structure composed exclusively of sheet metal, composites, machined parts, and numerical control machined parts, are shown in tabular form in Table 48. The learning rates for subassembly of high, medium and low learning structure composed exclusively of sheet metal, composites, machined parts and excluding numerical control machined parts are shown in tabular form in Table 49.

The learning curve values shown in these tables are the result of the review and comparative analysis of historical production learning experience. Samples of some of the learning curve data used appears in Figures 79 through 82. The program experience shown in Figure 79 shows that sheet metal detail fabrication has approximately 80% learning with machine shop detail fabrication learning being about 5% less at approximately 85%. These values are reflected in Table 48 as medium sheet metal and medium machine shop learning. Figure 80 for the C5A empennage shows learning associated with a sheet metal assembly task. This learning of about 75% is roughly 5% greater learning than the sheet metal detail fabrication learning of above. This plus 5% differential of subassembly to detail fabrication has been maintained in developing the learning curve values of Table 49. Learning associated with detail fabrication of numerically controlled skin planks is shown in Figure 81. From this figure it can be seen that this learning is very similar to medium machine shop learning for detail fabrication.

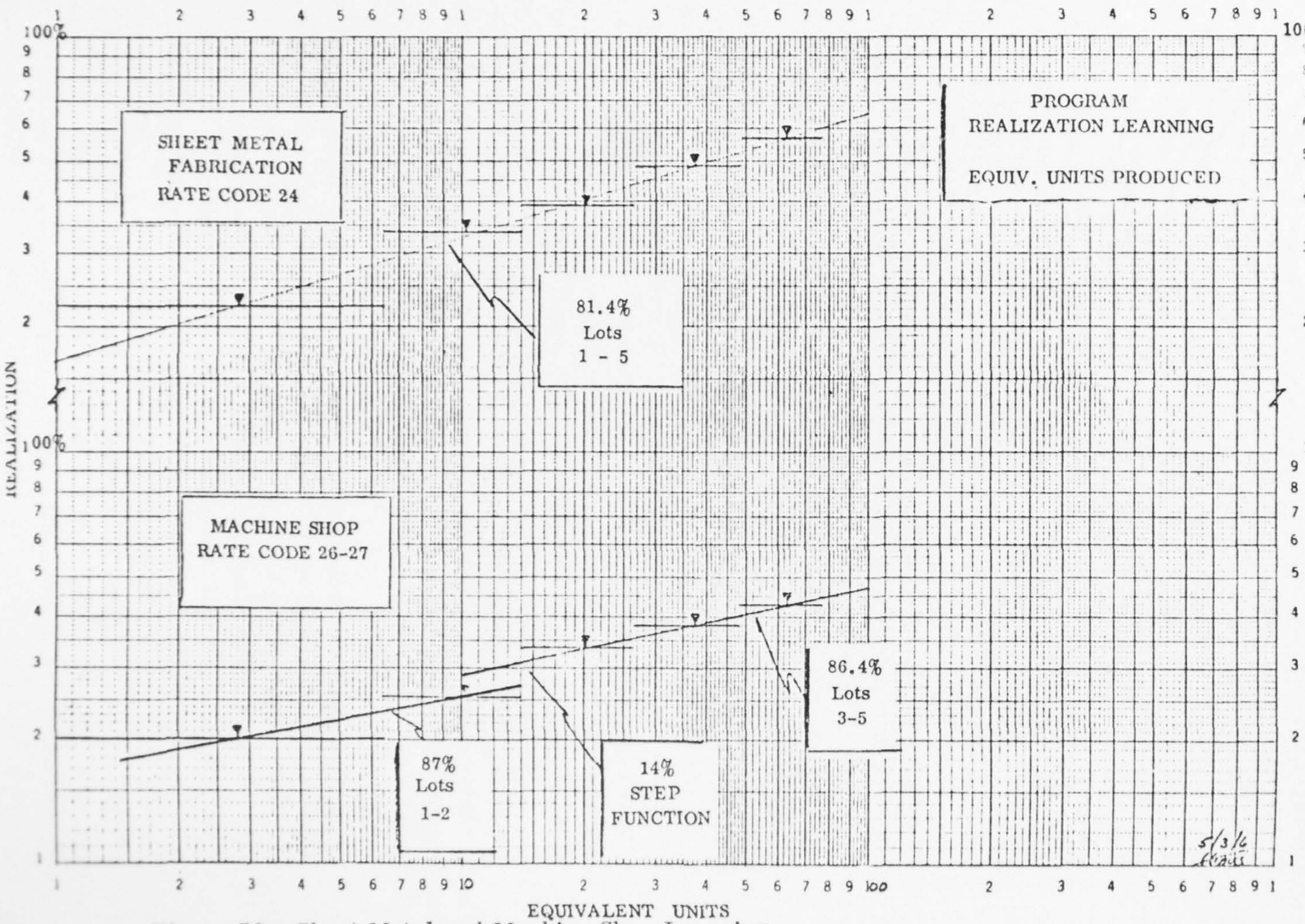


Figure 79. Sheet Metal and Machine Shop Learning.

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WEAPON SYSTEM COSTING METHODOLOGY IMPROVED STRUCTURAL COST ANAL--ETC(U)
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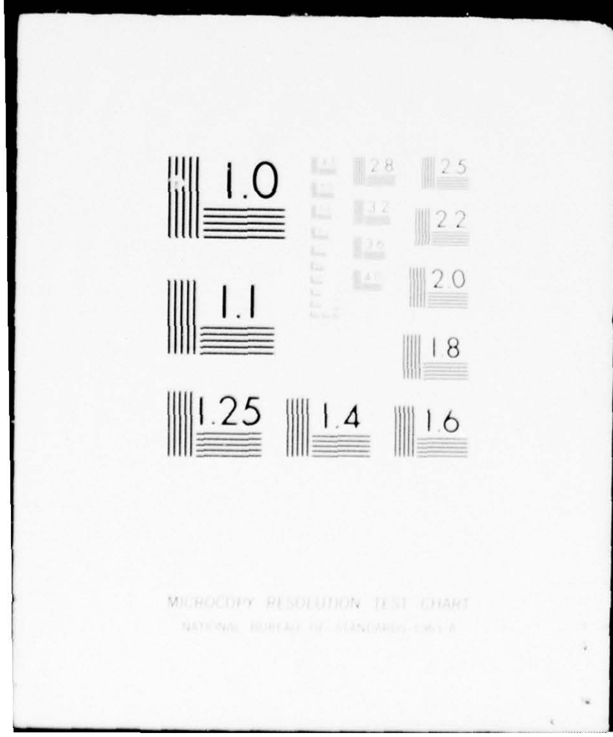
1.0
1.1
1.25
1.4
1.6
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2.0
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2.8
3.2
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

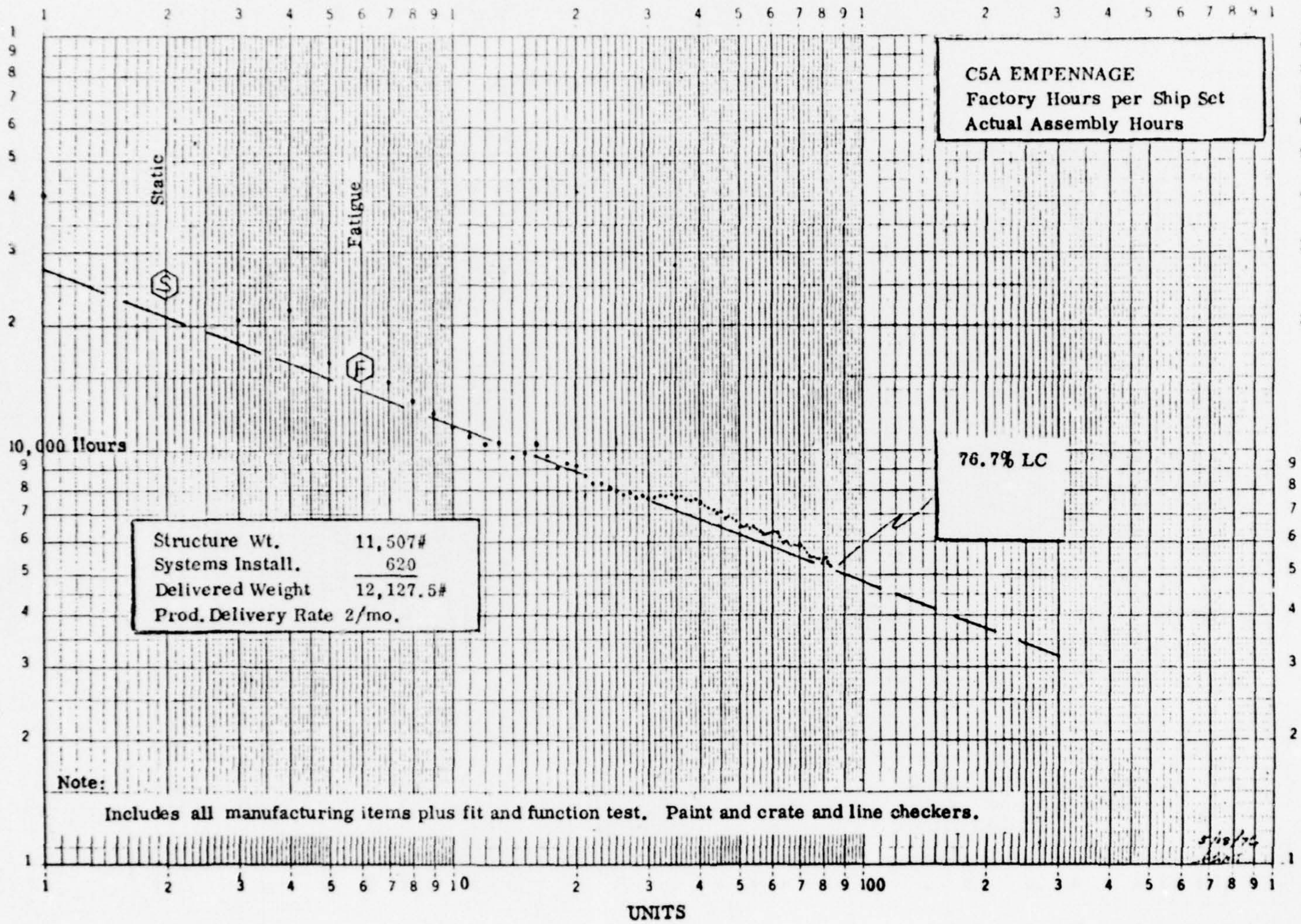

Figure 80. Assembly Learning.

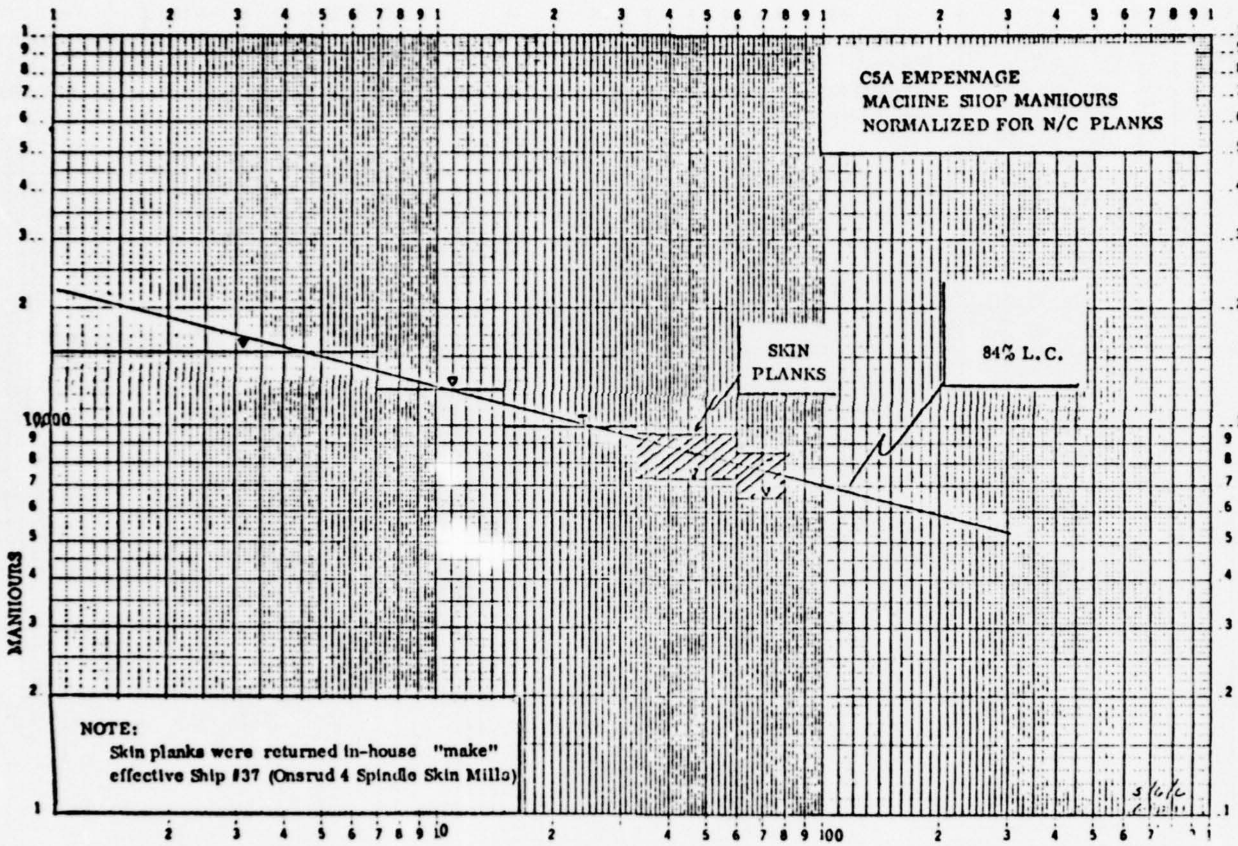

Figure 81. Numerical Control Learning.

Additional data on numerically controlled machining processes (Figure 82) indicates that very low learning (high percentage values) is occasionally experienced with numerically controlled manufacturing processes and selection of a numerically controlled machining process learning factor should reflect a consideration of this possibility.

Table 48

Detail Fabrication Learning

	Sheet Metal	Composites Shop	Machine Shop	Numerical Control
High	.75	TBD	.80	.80
Medium	.80*	TBD	.85	.85
Low	.85	TBD	.90	.90

*T. P. Wright, Factors Affecting the Cost of Airplanes, Journal of Aeronautical Sciences February 1936.

Note: T. P. Wright believed in a straight line cumulative average cost; whereas J. R. Crawford, at a later date,developed a straight line unit cost curve. The straight line unit cost curve is now widely accepted and is the equation formulation used in this current research.

Table 49

Subassembly Learning

	Sheet Metal	Composites Shop	Machine Shop	Numerical Control
High	.70	TBD	.75	N.A.
Medium	.75	TBD	.80	N.A.
Low	.80	TBD	.85	N.A.

The above Tables (48 and 49) are used to establish the specific learning associated with a specific piece of structure. Based on the specific type of structural elements used in given construction type, a learning curve value is determined. All of the construction types, except the built-up truss, are confined to one of four basic manufacturing activities: sheet metal, composites shop, machine shop and numerical control. The built-up truss requires a combination of manufacturing categories. The selection, development and tabulation of specific learning rates for model usage

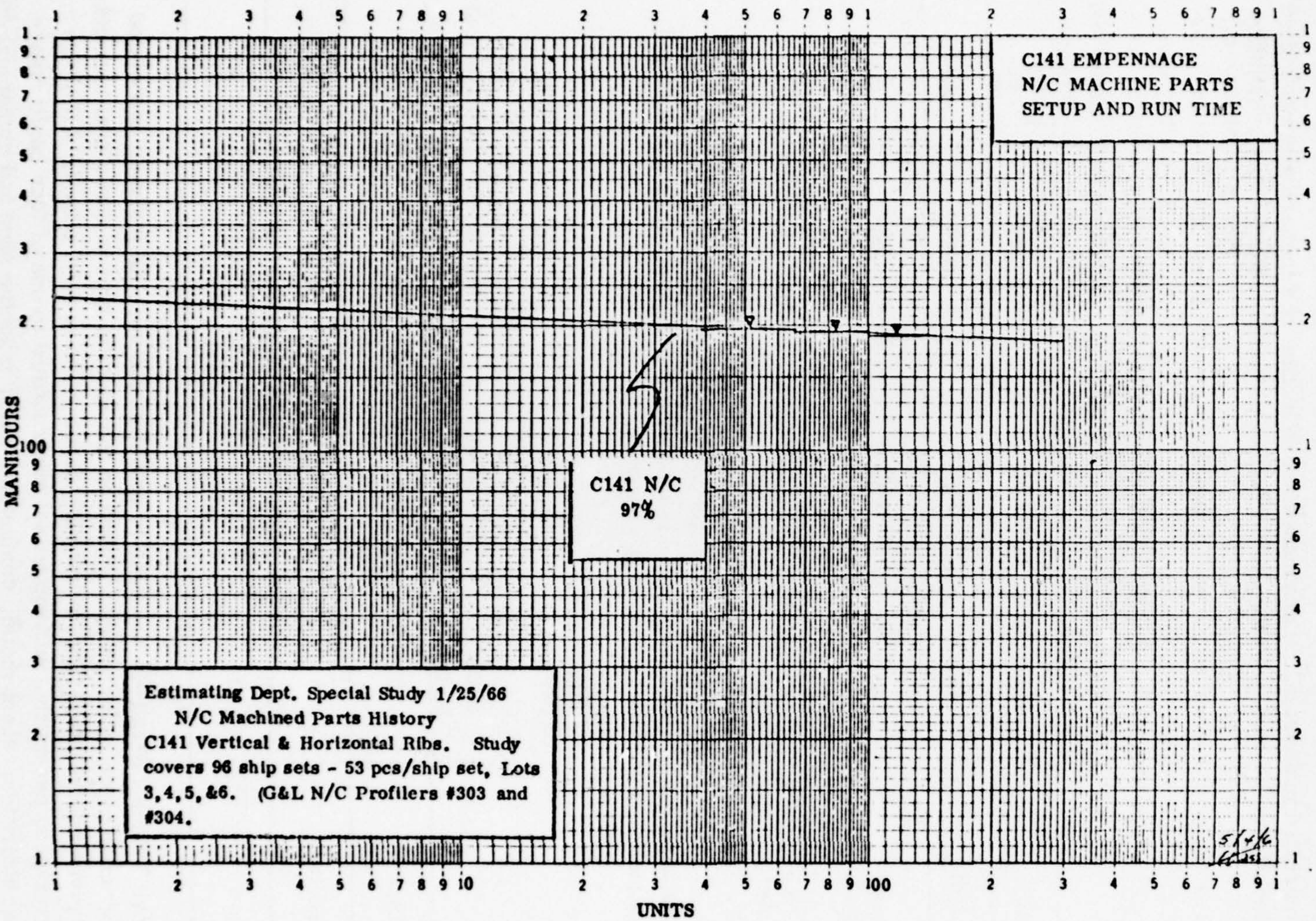

Figure 82. Limited Learning Numerical Control.

appears in Section 3.6.5

3.6.2 CONSTRUCTION TYPE ANALYSIS. The fundamental learning relationships developed in Section 3.6.1, above, provide the basic building blocks for development of airframe production learning on types of structure that represent a mixture of activities that are performed in the various shop areas. Ribs, spars, frames and longerons are produced, for purposes of the model, using six basic construction types: built-up web stiffener, built-up truss, sheet web, corrugated web, integral web stiffener and integral truss. Covers and skins are produced, for purposes of the model, using four basic construction types: built-up skin stringer, integral skin stringer, machined plate and sheet. Each of these construction types requires a specific type of shop activity or a mixture of different types of shop activity.

That a particular type of construction possibly requires combinations of specific types of shop activity is obvious from an examination of an aircraft production facility. A systematic, quantitative method of dealing with these combinations is, however, not obvious. The first question that must be answered is what is the purpose of the model. This necessarily involves the level of detail at which the model should be built. If a model is to be used for production line decision making, it must be very detailed and closely model the specific set of program requirements and particular unique production environment. If, however, a model is to be used for long range planning, it should be simple and reflect the major or "Pareto variables" that account for the most significant cost impacts. The model, for which the learning factors developed here will be used, is to be used for intermediate level decisions and as such represents a compromise between each of the above extremes of great detail and sparse detail. This intermediate level of detail still provides a wide range of modeling options. These options must be sorted and examined in light of theoretical considerations (such as cause and effect relationships between driving parameters and cost) and practical considerations (such as availability of data).

Initially, it was intended to identify learning factors at a level where a specific construction type and material type could be isolated. From a practical point of view, differentiation of learning by material type was unwise. Currently available learning data either doesn't differentiate learning by material type or indicates that different types of material exhibit essentially the same learning in a given application (Reference 14). For instance, a rib made of aluminum would require less time, on the average, to make than a rib made of titanium. The learning, however, would probably be the same on the two ribs since learning associated with producing large quantities of the same item would be the same. It is, of course, possible to produce a given structural item out of an inappropriate material and thereby provide a situation where significant differential learning can be achieved. Similar learning on two identical ribs made with different materials depends on appropriate material choice for that particular application at the outset. Material choice for a particular application, from the standpoint of learning, must be made on the basis of a detailed producibility analysis to ensure that a particular structural configuration can be efficiently made,

in large production quantities, from a given material. In that sense, the decision of what material to use for a particular piece of structure, from the standpoint of learning, must be made at a lower level than the current computer modeling program is designed. The magnitude of variables and the need for unique inputs of "engineering judgment" preclude a mechanical, computerized decision on material choice for a given piece of structure and its attendant learning. What is provided with this computer model is a quantitative feel for the relative magnitude of cost associated with different material selections. What must be borne in mind is the interactive relationship between a cost model of a given piece of structure and its actual design and production. The cost model provides valuable insights and a systematic framework for evaluating design alternatives; but, it can never be a substitute for human judgment. In a sense, the cost model can "guide but not decide." In the light of the above, it has been determined that construction type is more manageable and important in determining the learning rate on a particular piece of structure than is material type. The type of construction is a prime determinant of the area of a shop that a particular piece of structure is produced. If it is produced primarily in the sheet metal area, the potantial for significant learning exists since a great deal of people activity is involved in sheet metal operation. If a particular piece of structure is produced primarily in the machine shop area, less potential learning exists since activity is more constrained and controlled by machine operations. As a general observation, the greater the percentage of people activity as opposed to machine activity, the greater the potential for learning improvements. People learn how to produce things better and more efficiently whereas machines can to a very limited degree. The ratio of people to machine activity is closely linked to the type of construction. A built-up web stiffened rib, for instance, is mostly sheet metal. This involves a high percentage of people activity with corresponding high rates of learning. An integral web stiffener, on the other hand, is basically a solid piece of metal that has been hogged out by machine. This involves a low percentage of people activity with corresponding low rates of learning. The degree of learning that is experienced in a particular application is apparently intimately tied to the question of what percentage of the total work is performed by people. This question can be almost entirely answered by considering the type of construction to be used for a specific piece of structure. The other main consideration of material type appears to have a lesser impact on learning since the decision to produce by a labor intensive or capital intensive mode is relatively independent of the material. Most materials can be formed and worked using a variety of techniques and procedures that have varying degrees of human activity. The aspect of cost that is directly affected by material choice is the absolute level of cost. A titanium part for instance, with all other things being equal, is more expensive to produce than an aluminum one because titanium is harder and more difficult to work. Since the absolute level of cost is taken care of by the first unit cost part of the cost model, the learning portion of the cost model need only concern itself with the type of construction being used and not the material per se.

3.6.3 SECONDARY STRUCTURE LEARNING FACTORS. Secondary structure has been analyzed and grouped into the three categories of high, medium and low learning. The high learning category is composed of secondary structure that required a significant amount of detail fabrication and assembly labor. The medium category of learning is composed of structural items that are a combination of purchased and fabricated parts thereby providing less opportunity for in-house economies of production quantity. The low learning category is composed primarily of purchased fabricated parts and is relatively insensitive to production quantity. Table 50 is a summary of the learning categories and the specific elements of secondary structure associated with them. The specific values of learning for detail fabrication and subassembly were developed based on the elemental learning values developed for primary structure in Section 3.6.1. Three separate estimates were made using three different assumptions. The first assumption was that nominal values for learning as represented by machine shop conditions, could be representative of secondary structure. The second assumption was that higher learning, as represented by sheet metal shop conditions, is more representative of secondary structure. The third assumption was that each specific category should be evaluated separately to see if a representative pattern emerges. For the case of detail fabrication, the first assumption of machine shop type learning was in close agreement with the tailored estimate of what specific learning rates for high, medium and low learning would be appropriate. This can be seen from an examination of Table 51 which provides a side-by-side comparison of the resultant learning rates under the three different sets of assumptions. This correlation and the fact that variability in the data base and specific applications doesn't warrant more precise formulations led to the following values for detail fabrication secondary structure:

Detail Fabrication Secondary Structure Learning	High	.80
	Medium	.85
	Low	.90

For the case of subassembly, the first assumption of a machine shop analog and the tailored approach were comparable. The only difference being that in the case of relatively low learning the tailored approach yielded a five percent higher value of .90. Based on this assessment, the following values for subassembly of secondary structure have been determined to be appropriate:

Subassembly Secondary Structure Learning	High	.75
	Medium	.80
	Low	.90

Elements of secondary structure as categorized in Table 50 can now be identified with a specific learning dependent on whether the manufacturing task is detail fabrication or subassembly.

Table 50. Secondary Structure Groupings by Learning.

High	Pivots & Folds		
	High Lift Ducting	Speed Brakes	Slats
	Leading Edge	Fairings	Fuel Provisions
	Trailing Edge	Wing Box	Flaps
	Cockpit	Main LG Door	Pivots
	Cowling	Tips	Rudder
	Nose LG Door	Tail Attachment	Center Section
	Pylon	Attach Structure	Air Induction
	Ailerons	Spoilers	Elevators
Medium	Brakes	Drag Braces	Other
	Brake Controls	Engine Provisions	
	Wind Shield	Access Doors	
	Oleos	Duct Provisions	
	Axles	Stores Provisions	
	Hinges	Cabin Flooring	
	Access	Doors	
Low	Wheels		
	Tires		
	Balance Weights		
	Windows		

Table 51. Secondary Structure Detail Fabrication

	Assumption 1 Machine Shop	Assumption 2 Sheet Metal	Assumption 3 Tailored	Selected Values
High	.80	.75	.80	.80
Medium	.85	.80	.85	.85
Low	.90	.85	.90	.90

3.6.4 MATERIAL LEARNING FACTOR DEVELOPMENT. Material refers to all material that must be purchased by an airframe producer to construct an airframe. It includes raw material, forgings, purchased parts, subcontracted parts, and standard parts. Production learning takes place on all of the above mentioned items but in the case of standard parts, production is sufficiently out on the learning curve to effectively have a flat curve without further price benefits from larger production quantities. A similar, but less certain, situation exists for raw material purchases. Common raw materials such as aluminum and steel, are produced by stable mature processes that are relatively unaffected by anything less than huge purchase quantities. Quantity purchase discounts are available but these reflect marketing considerations rather than production learning per se. The exception would be new, high technology materials, such as composites, that represent new processes where the potential for learning is high. Due to the limited experience with large production quantities of composite materials definitive learning curve values for composite material procurement must await further experience and subsequent research.

For forgings, purchased parts, and subcontracted parts varying degrees of production learning take place. For forgings, the uniqueness and complexity of the forged parts affect the rate of learning. For purposes of modeling a nominal value of .90 can be used. Purchased parts represent items that can essentially be bought off the shelf without extensive design or rework. Complexity of parts and relatively high sensitivity of purchased parts manufacturers to sales volume allows a nominal value of .90 for modeling purposes. Subcontracted parts represent those pieces of airframe that have to be designed and built from scratch but for reasons of cost or production capability are built by someone other than the airframe contractor. Virtually the full benefits of production learning are realized and for purposes of modeling, a nominal value of

.85 is used. A summary of the above learning associated with the various material elements appears as Table 52. For convenience and a guide to the correct selection of material elements for a specific airframe configuration, a learning rate lookup table that parallels those for detail fabrication and subassembly has been prepared and appears as Table 53.

Table 52. Material Learning

Material Elements	Learning	Rate
A) Raw Material	No	.95*
B) Forgings	Yes	.90
C) Purchased Parts	Yes	.90
D) Subcontracted Parts	Yes	.85
E) Standard Parts **	No	1.00

*Quantity purchase benefits (Rate represents equivalent for common materials such as aluminum and steel.)

** Purchased in bulk and used as required.

Note: Above learning rates represent nominal values associated with specified element of material learning. Letter designations of Table 66 and above identify most probable material element associated with a given piece of structure.

3.6.5 LEARNING FACTOR MATRIX DEVELOPMENT. Learning factor matrices were developed for detail fabrication and subassembly that are built on the fundamental realtionships developed in Section 3.6.1. The matrices identify the specific learning factor that should be used as an input to the model for each primary and secondary structural element defined by the model. The first step in the development of the specific values within the matrices was to estimate at the rib, spar and cover level the percentage distribution of the various shop activities required to produce built-up web stiffener, built-up truss, sheet web, integral web stiffener, integral skin stringer, machined plate, etc., types of structure. The construction types identified in Appendix E of Reference(15) were evaluated to determine the types of shop activity associated with each one. The percentage distribution of the various types of shop activity were then used as weighting factors to develop a composite learning built on the fundamental learning relationships developed in Section 3.6.1.

Table 53. Learning Factors for Material for Primary and Secondary Structure

Symbol	Wing		Horizontal		Vertical		Fuselage		Nacelle		Landing Gear	
PC11	Ribs	*	Ribs	*	Ribs	*	Frames	*	Not used		Not used	
PC12	Spars	*	Spars	*	Spars	*	Longerons	*	Not used		Not used	
PC13	Covers	A	Covers	A	Covers	A	Covers	A	Not used		Not used	
PC14	Not used		Not used		Not used		Not used		Not used		Not used	
PC15	Leading Edge	A	Leading Edge	A	Leading Edge	A	Cockpit	A	Cowling	A	Brakes	C
PC16	Trailing Edge	A	Trailing Edge	A	Trailing Edge	A	Nose LG Door	D	Pylon	A	Brake Cont.	C
PC17	Ailerons	A	Fairings	A	Fairings	A	Wing Box	A	Main LG Door	D	Wheels	C
PC18	Fairings	A	Tips	A	Tips	A	Tail Attachment	A	Not used		Tires	C
PC19	Tips	A	Attach Structure	A	Attach Structure	A	Windshield	C	Not used		Oleos	C
PC110	Spoilers	A	Access	A	Access	A	Main LG Door	D	Not used		Axles	C
PC111	Flaps	A	Hinges	A	Hinges	A	Fuel Provisions	D	Not used		Drag Braces	D
PC112	Attach Structure	A	Pivots	A	Rudder	A	Engine Provisions	D	Not used		Not used	
PC113	Access Doors	A	Center Section	A	Not used		Duct Provisions	A	Not used		Not used	
PC114	Air Induction	A	Elevators	A	Not used		Stores Provisions	A	Not used		Not used	
PC115	High-Lift Ducting	A	Balance Weights	C	Not used		Speed Brakes	A	Not used		Not used	
PC116	Slats	A	Not used		Not used		Cabin Flooring	A	Not used		Not used	
PC117	Hinges	A	Not used		Not used		Windows	C	Not used		Not used	
PC118	Pivots & Folds	A	Not used		Not used		Doors	D	Not used		Not used	
PC119	Center Section	A	Not used		Not used		Not used		Not used		Not used	
PC120	Other	A	Not used		Not used		Not used		Not used		Not used	
PC121	Not used		Not used		Not used		Not used		Not used		Not used	

*No learning unless forgings are used extensively. (Nominal value with forgings = .90)

A, B, C, D & E; see Table 59.

Note: Most raw material exhibits quantity purchase discount but not learning per se. Quantity purchase discounts vary from none to significant depending on the type of material and current market conditions.

Evaluation of the various types of construction revealed that only the built-up truss type of construction had significant cross category fabrication activity requiring a composite learning rate.

Engineering judgment was used to determine high, medium and low classification within a given shop activity. The weighting calculations and resultant learning rates for a given type of construction have been tabulated in Tables 54 and 55. The higher learning rates associated with subassembly are due to the less structured nature of the subassembly task and attendant opportunity for improvement over time and quantity produced. The above tables provide all the learning rates associated with the primary structure of ribs, spars, frames, bulkheads, longerons, covers and skins.

The secondary structure composed of the items identified in Section 3.6.3 have been summarized to provide a simple look up table for all structure. These look up tables appear as Tables 56 and 57, providing learning factors for detail fabrication and subassembly, respectively.

Table 54. Learning Rates for Detail Fabrication Construction Types

	A	B	C	D	E	F
Ribs Spars Frames Bulkheads Longerons PC11 or PC12	Built-Up Web Stiffener 1.0*×.75**=.75	Built-Up Truss .8*×.80**= .64 .2*×.85**= .17 .81	Sheet Web 1.0*×.85**=.85	Corrugated Web 1.0*×.85**= .85	Integral Web Stiffenor 1.0*×.85**=.85	Integral Truss 1.0*×.85**=.85
	A	B	C	D	E	
Covers Skins PC13	Built-Up Skin Stringer 1.0*×.80**=.80	Integral Skin Stringer 1.0*×.85**=.85	Machined Plate 1.0*×.85**=.85	Sheet 1.0*×.85**=.85	Sandwich TBD	

*Relative Distribution of Shop Activity
**Learning Associated With That Type of Shop Activity and Construction

Table 55. Learning Rates for Subassembly Construction Types

	(A) Built-Up Web Stiffener	(B) Built-Up Truss	(C) Sheet Web	(D) Corrugated Web	(E) Integral Web Stiffener	(F) Integral Truss
Ribs Spars Frames Bulkheads Longerons PC 21 or PC 22	1.0* × .70** = .70	.8 × .75** = .60 .2 × .80** = .16 .76	1.0* × .80** = .80	1.0* × .80** = .80		

	(A) Built-up Skin Stringer	(B) Integral Skin Stringer	(C) Machined Plate	(D) Sheet	(E) Sandwich
Covers Skins PC 23	1.0* × .75** = .75		1.0* × .80** = .80	1.0* × .80** = .80	TBD

* Relative Distribution of Shop Activity

** Learning Associated with that type of Shop Activity and Construction

Table 56. Learning Factors for Detail Fabrication of Secondary Structure

Symbol	Wing		Horizontal		Vertical		Fuselage		Nacelle		Landing Gear	
PC11	Ribs	*	Ribs	*	Ribs	*	Frames	*	Not Used		Not used	
PC12	Spars	*	Spars	*	Spars	*	Longerons	*	Not Used		Not Used	
PC13	Covers	*	Covers	*	Covers	*	Covers	*	Not Used		Not Used	
PC14	Not Used		Not Used		Not Used		Not Used		Not Used		Not Used	
PC15	Leading Edge	.80	Leading Edge	.80	Leading Edge	.80	Cockpit	.80	Cowling	.80	Brakes	.85
PC16	Trailing Edge	.80	Trailing Edge	.80	Trailing Edge	.80	Nose LG Door	.80	Pylon	.80	Brake Controls	.85
PC17	Ailerons	.80	Fairings	.80	Fairings	.80	Wing Box	.80	Main LG Door	.80	Wheels	.90
PC18	Fairings	.80	Tips	.80	Tips	.80	Tail Attachment	.80	Not Used		Tires	.90
PC19	Tips	.80	Attach Structure	.80	Attach Structure	.80	Windshield	.85	Not Used		Oleos	.85
PC110	Spoilers	.80	Access	.85	Access	.85	Main LG Door	.80	Not Used		Axles	.85
PC111	Flaps	.80	Hinges	.85	Hinges	.85	Fuel Provisions	.80	Not Used		Drag Braces	.85
PC112	Attach Structure	.80	Pivots	.80	Rudder	.80	Engine Provisions	.85	Not Used		Not Used	
PC113	Access Doors	.85	Center Section	.80	Not Used		Duct Provisions	.85	Not Used		Not Used	
PC114	Air Induction	.80	Elevators	.80	Not Used		Stores Provisions	.85	Not Used		Not Used	
PC115	High-Lift Ducting	.80	Balance Weights	.90	Not Used		Speed Brakes	.80	Not Used		Not Used	
PC116	Slats	.80	Not Used		Not Used		Cabin Flooring	.85	Not Used		Not Used	
PC117	Hinges	.85	Not Used		Not Used		Windows	.90	Not Used		Not Used	
PC118	Pivots & Folds	.80	Not Used		Not Used		Doors	.85	Not Used		Not Used	
PC119	Center Section	.80	Not Used		Not Used		Not Used		Not Used		Not Used	
PC120	Other	.85	Not Used		Not Used		Not Used		Not Used		Not Used	
PC121	Not Used		Not Used		Not Used		Not Used		Not Used		Not Used	

*See Table 61

Table 57. Learning Factors for Subassembly of Secondary Structure

Symbol	Wing		Horizontal		Vertical		Fuselage		Nacelle		Landing Gear	
PC11	Ribs	*	Ribs	*	Ribs	*	Frames	*	Not used		Not used	
PC12	Spars	*	Spars	*	Spars	*	Longerons	*	Not used		Not used	
PC13	Covers	*	Covers	*	Covers	*	Covers	*	Not used		Not used	
PC14	Not used		Not used		Not used		Not used		Not used		Not used	
PC15	Leading Edge	.75	Leading Edge	.75	Leading Edge	.75	Cockpit	.75	Cowling	.75	Brakes	.80
PC16	Trailing Edge	.75	Trailing Edge	.75	Trailing Edge	.75	Nose LG Door	.75	Pylon	.75	Brake Cont.	.80
PC17	Ailerons	.75	Fairings	.75	Fairings	.75	Wing Box	.75	Main LG Door	.75	Wheels	.90
PC18	Fairings	.75	Tips	.75	Tips	.75	Tail Attachment	.75	Not used		Tires	.90
PC19	Tips	.75	Attach Structure	.75	Attach Structure	.75	Windshield	.80	Not used		Oleos	.80
PC110	Spoilers	.75	Access	.80	Access	.80	Main LG Door	.75	Not used		Axles	.80
PC111	Flaps	.75	Hinges	.80	Hinges	.80	Fuel Provisions	.75	Not used		Drag Braces	.80
PC112	Attach Structure	.75	Pivots	.75	Rudder	.75	Engine Provisions	.80	Not used		Not used	
PC113	Access Doors	.80	Center Section	.75	Not used		Duct Provisions	.80	Not used		Not used	
PC114	Air Induction	.75	Elevators	.75	Not used		Stores Provisions	.80	Not used		Not used	
PC115	High-Lift Ducting	.75	Balance Weights	.90	Not used		Speed Brakes	.75	Not used		Not used	
PC116	Slats	.75	Not used		Not used		Cabin Flooring	.80	Not used		Not used	
PC117	Hinges	.80	Not used		Not used		Windows	.90	Not used		Not used	
PC118	Pivots & Folds	.75	Not used		Not used		Doors	.80	Not used		Not used	
PC119	Center Section	.75	Not used		Not used		Not used		Not used		Not used	
PC120	Other	.80	Not used		Not used		Not used		Not used		Not used	
PC121	Not used		Not used		Not used		Not used		Not used		Not used	

*See Table 62

SECTION IV

COMPUTER PROGRAM CHANGES

The methodology changes discussed in the above sections resulted in changes to the estimating relationships and to the various input tables. In the first case, corresponding computer program changes are required. Assembly CER modifications, commonality effects, and production rate effects produced such changes. Changes to the input tables do not require computer program changes.

It is envisioned that the existing program will be retained in its present form, then as an additional operational mode, an alternative set of model cards will be produced to provide an expanded analysis capability. Computer program changes are being effected by AFFDL personnel.

4.1 ASSEMBLY CERs

Equation (7) Hole Drilling - Aero Surfaces or Fuselage becomes:

$$H_i = 2\left[(RP)^R \ (RN)^Q + (SPE)^R \ (SNE + SNI)^Q\right] (HD) \ (TJ4) \left(\frac{AU}{AP}\right)$$

The following F-cards changes are necessary:

$$F\ 16\ 4\ (15.1) * HD * TJ4 * \left(\frac{AU}{AP}\right) * 2$$

$$F\ 17\ 4\ (15.4) * HD * TJ4 * \left(\frac{AU}{AP}\right) * 2$$

$$F\ 18\ 4\ (15.7) * HD * TJ4 * \left(\frac{AU}{AP}\right) * 2$$

Equation (9) Fastener Installation - Aero Surfaces or Fuselage becomes:

$$H_i = 2\left[(RP)^R \ (RN)^Q + (SNE + SNI)^Q\right] (HFI) \ (TJ4) \ (FF2) \left(\frac{IF}{IP}\right)$$

OR

$$H_i = 2\left[(RP)^R \ (RN)^Q + (SNE + SNI)^Q\right] (HFI) \ (TJ4) \ (FF2) \left(\frac{AU}{AP}\right)$$

To accomplish the above, duplicate F-cards are to be used alternatively depending on whether automatic riveting or interference fit fasteners are being used. This gives rise to the following additional F-cards:

$$\text{F 16 6 (15,1) * HFI * TJ4 * FF2 * } \left(\frac{\text{IF}}{\text{IP}}\right) \text{ * 2}$$

$$\text{F 16 6 (15,1) * HIF * TJ4 * FF2 * } \left(\frac{\text{AU}}{\text{AP}}\right) \text{ * 2}$$

F 17 6 Two additional cards, same as F 16 6, except (15,5) replaces (15,1)

F 18 6 Two additional cards, same as F 16 6, except (15,7) replaces (15,1).

4.2 COMMONALITY EFFECTS

Evaluation of commonality effects requires the substitution of an F-card calculation for the Z-card calculations of the existing program. This switch is necessary because there are no suitable Z-card terms to match the forms of the commonality equations, i.e., those described in Section 3.4.1. Use of the F-card format requires that the production cost run-out be accomplished using a log-linear cumulative average definition of the log-linear estimating curve. Since the model itself is based on a log-linear unit cost concept, an additional term is introduced on the F-card to provide for conversion from log-linear cumulative average to log-linear unit. This term is simply the ratio of the cum average to unit curve as obtained from Reference 16.

The substitution for commonality begins with Wing RDT&E Costs, SAV matrix line 65. This becomes F 65 1 (Equation A) where Equation A is now defined as,

$$\text{F 65 1 } \Big(\text{(1-Pc) * } R_D \text{ * (SS) ** b + (Pc * } R_D\text{/NCR * (SS * NCR) ** b)}\Big)$$

$$\text{* CR}$$

where the terms are as defined for Equation A in Section 3.4.1, except that the term CR is the log-linear cumulative average to log-linear unit ratio.

In a similar fashion:

F 65 2 (Equation F) * CR
F 66 1 (Equation B) * CR
F 66 2 (Equation G) * CR
F 67 1 (Equation C) * CR
F 67 2 (Equation H) * CR
F 71 1 (Equation K) * CR
F 71 2 (Equation K) * CR
F 72 1 (Equation K) * CR
F 72 2 (Equation K) * CR
F 73 1 (Equation K)
F 73 2 (Equation K)
F 74 1 (Equation K)
F 74 2 (Equation K)
F 75 1 (Equation K)
F 75 2 (Equation K)
F 76 1 (Equation K)
F 76 2 (Equation K)
F 77 1 (Equation K) * CR

F 77 2 (Equation K) * CR
F 78 1 (Equation K)
F 78 2 (Equation K)
F 79 1 (Equation K)
F 79 2 (Equation K)
F 80 1 (Equation K)
F 80 2 (Equation K)
F 81 1 (Equation K)
F 81 2 (Equation K)
F 82 1 (Equation K)
F 82 2 (Equation K)
F 83 1 (Equation K)
F 83 2 (Equation K)
F 84 1 (Equation K)
F 84 2 (Equation K)
F 85 1 (Equation K)
F 85 2 (Equation K)
F 86 1 (Equation K)
F 86 2 (Equation K) * CR

Starting with line 126 through Z 142 for the Horizontal Stabilizer, RDT&E Costs, a series of F-card substitutions are made similar to that for the Wing.

For the Vertical Stabilizer, F-cards are formulated in a similar manner for substitution for Z-cards Z 175 through Z 189.

For the Fuselage, F-cards are formulated as follows:

F 235 1 (Equation D) * CR
F 235 2 (Equation I)
F 236 1 (Equation E)
F 236 2 (Equation J)
F 237 1 (Equation F)
F 237 2 (Equation H)
F 241 1 (Equation K)
F 241 2 (Equation K)
F 242 1 (Equation K) * CR

and so forth through Z 254 2.

For nacelles, only Equation K is used. F-cards are required for Z-cards Z 285 1 through Z 287 2. This is also true for Landing Gear for Z-cards Z 318 1 through Z 324 2. The term * CR is, of course, applied.

The above covers RDT&E production costs. For Recurring Production Costs, substitutions begin with Z 335 1. However, since the Recurring Production quantity is in addition to the RDT&E production quantity, further development of the series of equations is required. This gives rise to an additional series of equations, which are designated as Equation A', etc.

Equation A' (and all other equations in the prime series) are derived by expansion of the original equations to encompass the recurring production increment. Each of the equations are of the same form. Equation A' is used for purposes of illustration.

Equation A' was as follows:

$$\text{Ribs Cost} = (1 - Pc)\ (R_D)\ (SS)^b + \frac{Pc\ (R_D)}{NCR}\left[SS\ (NCR)\right]^b,$$

with the terms as defined in Item 1 above. For the new series, SS takes on the additional definition: RDT&E production quantity. This equation can be arranged in the following form.

$$\text{Ribs cost} = SS^b\left[(1 - Pc)\ R_D + \frac{Pc\ (R_D)}{(NCR)^{1-b}}\right],$$

for RDT&E production.

The quantity of Recurring Production is the difference between the total quantity and the the RDT&E quantity, or

$$\left[SS_T^b - SS^b\right].$$

For Recurring Production then, we have as Equation A',

$$\text{Ribs cost} = \left[SS_T^b - SS^b\right]\left[(1 - Pc)\ R_D + \frac{Pc\ (R_D)}{(NCR)^{1-b}}\right],$$

or in a further simplified form:

$$\text{Ribs cost} = \left[SS_T^b - SS^b\right]\left[R_D\right]\left[1 - Pc + Pc\,(NCR)^{b-1}\right].$$

SS_T refers to the total quantity produced, including both RDT&E and Production.

The required programming changes for Production are as follows:

Wing

F 335 1 (Equation A') * CR
F 335 2 (Equation F')
F 336 1 (Equation B')
F 336 2 (Equation G')
F 337 1 (Equation C')
F 337 2 (Equation H')
F 341 1 (Equation K')
F 342 2 (Equation K') * CR

And so forth for both SAV matrix columns 1 and 2 through F 356 2.

Horizontal Stabilizer

For Horizontal Stabilizer, the substitution of F-cards begins with F 366 1 and proceeds through F 372 2.

Vertical Stabilizer

For Vertical Stabilizer, the substitution begins with F 392 1 through F 405 2.

Fuselage

For Fuselage the Production cost substitutions are:

F 416 1 (Equation D') * CR
F 416 2 (Equation I')
F 417 1 (Equation E')
F 417 2 (Equation J')
F 418 1 (Equation F')
F 418 2 (Equation H')
F 422 1 (Equation K') * CR

and so forth through F 435 2.

Nacelles

Only Equation K' is used. F-cards are required for lines F 446 1 through F 448 2 in the established pattern.

Landing Gear

Only Equation K' is used. F-cards are required for lines F 458 1 through F 464 2.

The above series of changes is for Recurring Production for the first quantity estimated. A second quantity is estimated using matrix lines Z 476 1 through Z 604 2. F-card substitutions should be provided for these in the same way as for the above series.

The term b in the above is defined as follows:

$$b = b' + 1, \text{ where}$$

$b' = \dfrac{\log LC}{\log 2}$ and LC is the learning curve expressed as a decimal fraction. This means that each of the equations gives cumulative total costs.

4.3 PRODUCTION RATE EFFECTS

It may not be necessary to modify the computer program to provide for evaluation of production rate effects. If it can be assumed that any structural trade-off will be accomplished under a constant rate of production, it would seem to be possible to evaluate rate effects external to the model using the equation provided. This would seem likely since production rate is a question of programmatics rather than design trade-off.

If it is desired, however, to incorporate this capability in the present program, an alternative set of F-cards is required. The simplest way to describe these changes is by reference to Appendix A of Reference 1. Each First Unit Cost section requires a set of alternative F-cards. Each alternative card is formulated by adding * (1.16 - .16R) to each F-card affected. The term R equals actual Rate divided by Ideal Rate. The lines and columns requiring this change are as follows:

Wing

F 31 1	F 39 2	F 44 2	F 49 1
F 31 2	F 40 1	F 45 1	F 49 2
F 32 1	F 40 2	F 45 2	F 50 1
F 32 2	F 41 1	F 46 1	F 50 2
F 33 1	F 41 2	F 46 2	F 51 1
F 33 2	F 42 1	F 47 1	F 51 2
F 38 1	F 42 2	F 47 2	F 52 1
F 38 2	F 43 1	F 48 1	F 52 2
F 39 1	F 43 2	F 48 2	F 53 1
	F 44 1		F 53 2

Horizontal Stabilizer

F 100 1	F 106 2	F 110 1	F 113 2
F 100 2	F 107 1	F 110 2	F 114 1
F 101 1	F 107 2	F 111 1	F 114 2
F 101 2	F 108 1	F 111 2	F 115 1
F 102 1	F 108 2	F 112 1	F 115 2
F 102 2	F 109 1	F 112 2	F 116 1
F 106 1	F 109 2	F 113 1	F 116 2

Vertical Stabilizer

F 151 1	F 153 2	F 160 1	F 163 1
F 151 2	F 158 1	F 160 2	F 163 2
F 152 1	F 158 2	F 161 1	F 164 1
F 152 2	F 159 1	F 161 2	F 164 2
F 153 1	F 159 2	F 162 1	F 165 1
		F 162 2	F 165 2

Fuselage

F 201 1	F 209 2	F 213 2	F 218 1
F 201 2	F 210 1	F 214 1	F 218 2
F 202 1	F 210 2	F 214 2	F 219 1
F 202 2	F 211 1	F 215 1	F 219 2
F 203 1	F 211 2	F 215 2	F 220 1
F 203 2	F 212 1	F 216 1	F 220 2
F 208 1	F 212 2	F 216 2	F 221 1
F 208 2	F 213 1	F 217 1	F 221 2
F 209 1		F 217 2	

Nacelles

F 271 1	F 272 2
F 271 2	F 273 1
F 272 1	F 273 2

Landing Gear

F 301 1	F 304 2
F 301 2	F 305 1
F 302 1	F 305 2
F 302 2	F 306 1
F 303 1	F 306 2
F 303 2	F 307 1
F 304 1	F 307 2

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A series of studies undertaken to provide an improved state-of-the-art capability for estimating the cost of aircraft airframes and basic structures was successfully completed. Six separate studies were involved. In three of these computer program changes were involved. For the remaining three, improvements were handled by means of additions to the program input tables.

This contract is a follow-on to the contract study described in a previous technical report, Reference 1. That study resulted in the development of a trade study costing methodology that was designed to systematically estimate cost variations due to changes in type of material and type of construction. The method was designed and shown to be feasible for trade study costing for structural design-to-cost problems during the preliminary design phase of a program. The solution included a cost model that makes estimates based on physical parameters, type of material, and type of construction and assembly of structural components such as ribs, spars, covers, longerons, frames, etc. At the end of this previous study, the model was still considered to be in a development status and a series of additional studies were recommended. Resulting conclusions and recommendations are discussed below.

1. The first study was to develop additional complexity factors for technologies and materials represented by an advanced manned aerospace vehicle structure (AMAVS), the advanced strategic bomber wing carry-through box. The trade study cost estimating method was structured around a concept that would provide for the incorporation of a future data base with its established cost estimating factors. In the study the cost data resulting from the AMAVS program advanced technology concepts were plotted against cost data from more conventional types of structure. If the conclusions arrived at from a single data point are to be taken at face value, the results are noteworthy. The advanced technology, in almost every case, resulted in substantially lower cost while at the same time providing dramatic improvements in structural performance. The principal material involved was 10 nickel steel.

   This conclusion cannot be made, however, without noting that it is based on a single data sample. The data was very carefully collected and has high credibility as a single data point; however, the recommendation is made that additional examples of this technology be evaluated in order to assess the credibility of the study conclusion.

2. In the second study task, raw material cost estimating relationships (CERs) were modified to increase their sensitivity to material product form and type of

scrappage. The updated CERs expand the number of terms used to estimate raw material from 2 to 4. The additional terms provide for an explicit evaluation of the material form factor and provide a capability for redefining scrappage factor as a combination of yield and manufacturing usage variance. This provides the basis for additional data collection related to yield factors, mill prices and product form factors.

3. Under the previous method, assembly costs are estimated by a series of CERs in a sequence that represents a generalized concept of the assembly process developed for modeling purposes. This sequence was not changed, but the CERs were reviewed to determine the changes necessary to provide a capability for evaluating the varied additional assembly techniques of: automatic riveting, interference-fit fasteners, diffusion bonding and adhesive bonding. Additions were made to both the cost estimating relationships and to the input factors. This applied primarily to types of construction involving built-up components as opposed to integral structures. Further study of this topic is recommended.

4. A means of evaluating commonality within structural components was developed. Commonality refers to the degree to which a piece of structure or other system is composed of similar or identical parts. High commonality implies a high degree of part similarity and low commonality, the reverse. A complete set of equations was developed. These are entered into the model in a way so that they may or may not be used in a given structural evaluation.

5. An optional capability for assessing production rate effects was added to the model. It was found that this effect can be stated as a relationship between the actual production rate and the ideal production rate for the facility in which the work is being accomplished. Further testing of these results is recommended.

6. The trade study cost estimating method makes provision for use at a detailed level of alternative learning curve projections. The furnishing of factors had not been a part of the previous study. Based on the contractor's experience, specific factors have now been provided. It is thus possible to specify learning according to type of construction and material by primary and secondary structure.

7. The above improvements can be entered into the cost model computer program on a selective basis. This entails retaining the existing model and formulating model cards for each of the specified changes. Instructions for such changes have been developed.

8. As a general recommendation, the following are suggested for further improvement of the methodology:

   a. Design and run test cases for the program changes described.

b. Collect cost data and make calibration runs on actual fighter programs.

c. Develop an estimating structure and combine the TEASE (Techniques for Evaluating Aerospace Structural Elements) and STEP (Structural Technology Evaluation Program) programs. Interrelate input requirements.

d. Develop CERs to estimate the cost of tooling for various structural concepts.

e. Define methodology and requirements for expanding complexity factor tables.

f. Develop additional learning curve factors for composite materials.

APPENDIX A

TRADE STUDY CERS AND DEFINITIONS

This appendix consists of a listing of basic CER forms and the accompanying set of cost definitions. Two numbering series are used to cross-reference these CER forms to previous descriptions: (1) the first column which references a series of figures depicting cost printouts and identifying the corresponding CERs, and (2) the second column, which references the assignement of equation numbers used in Reference 1. The figure references in the first column are also those used in Reference 1.

FIRST UNIT COST

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
1	(1)	Detail Fabrication Hours for Primary Structure:	Definition: The manufacturing tasks required for machine shop and sheet metal shop fabrication of parts for ribs, spars, frames, longerons and covers, and process per specification.

$$H_i = \left[\frac{W_i\,CF_i + W_i\,CF_i + W_i\,CF_i}{WT_i} \right] (HF_i)\,(WT_i)^{E_i} \quad (1)$$

where

- H_i = fabrication hours for ribs, frames, spars, longerons and covers corresponding to element inputs
- W_i = a series of weights for the components estimated: ribs, frames, spars, longerons, and covers
- CF_i = a series of complexity factors corresponding to component type related to fabrication
- WT_i = computer summation of the weights:
  - WT = Sum of rib weights
  - WT1 = Sum of spar weights
  - WT2 = Sum of cover weights
- HF_i = a series of reference cost per pound values for ribs, frames, spars, longerons, & covers related to fabrication labor
- E_i = a series of weight scaling exponents for ribs, frames, spars, longerons, and covers related to fabrication labor

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
1	(2)	Subassembly Hours for Primary Structure:	Definition: The manufacturing tasks required for the assembly of ribs, spars, frames, longerons and covers. A sequence of operations leading to the creation of the particular subassembly is assumed. It includes all assembly not controlled by Operation Inspection Logs.

$$H_i = \left[\frac{W_i\,CM_i + W_i\,CM_i + W_i\,CM_i}{WT_i} \right] (HF_i)\,(WT_i)^{E_i} \quad (2)$$

where

- H_i = subassembly hours for ribs, frames, spars, longerons and covers corresponding to variable inputs
- W_i = weights used for detail fabrication
- CM_i = a series of complexity factors corresponding to component type related to subassembly
- WT_i = computer summation of weights
- HF_i = a series of reference cost per pound values for ribs, frames, spars, longerons, and covers related to subassembly labor
- E_i = a series of weight scaling exponents for ribs, frames, spars, longerons, and covers related to subassembly labor

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
2	(10)	Detail Fabrication Hours for Secondary Structure: $$H_i = CB_i (WC_i) (WD_i)^{E_i}$$ where H_i = detail fabrication hours, secondary structure CB_i = a series of complexity factors corresponding to component type related to fabrication WC_i = a series of reference cost per pound values for secondary structure components related to fabrication labor WD_i = a series of weights for the secondary structure components being estimated E_i = a series of weight scaling exponents for secondary structure components related to fabrication labor.	Definition: The manufacturing tasks required for machine shop and sheet metal fabrication of parts for secondary structure elements.
2	(11)	Subassembly Hours for Secondary Structure: $$H_i = CC_i (WF_i) (WD_i)^{F_i}$$ where H_i subassembly hours, secondary structure CC_i a series of complexity factors corresponding to component type related to subassembly WF_i a series of reference cost per pound values for secondary structure components related to fabrication labor WD_i the same series of weights as for detail fabrication F_i a series of weight sealing exponents for secondary structure components related to subassembly labor	Definition: The manufacturing tasks required for the bench assembly and subassembly of secondary structure components. A sequence of operations leading to the creation of the secondary structure component (such as the leading edge, for example) is assumed.

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
3		Basic Structure Major Assembly Labor:	Definition: This consists of OIL controlled assembly accomplished in major fixture and the operations required for movement from station to station. Assemblies are subdivided into basic structure and secondary structure. This is the distinction, for example, between creating the structural box and attaching secondary structure components thereto. Each of the basic operations are addressed.
		<u>Transporting and Positioning - Aero Surfaces or Fuselage</u>	Definition: Includes movement between stations, and positioning and loading into fixtures.
	(3)	$H_1 = \left[(WT_1/2)\,(HSA1) + (HSA2)\,(CN + RN + SNE + SNI)^Q\right] \times 2$	
	(4)	<u>Panel Fit and Trim - Aerodynamic Surfaces</u>	Definition: The fitting of skin panels and other trim operations.

Equation (3)

$$H_1 = \left[(WT_1/2)\,(HSA1) + (HSA2)\,(CN + RN + SNE + SNI)^Q\right] \times 2$$

where

- H_1 = primary structure major assembly hours for aerodynamic surfaces structural boxes and fuselage basic structure.
- WT_1 = weights used for detail fabrication of complete wing or fuselage.
- HSA1 = assembly hours per unit weight for transporting and positioning
- HSA2 = assembly hours per subassembly for transporting and positioning
- CN = number of cover panels (one side, upper and lower)
- RN = number of ribs or frames (one side, upper and lower)
- SNE = number of external spars (one side, upper and lower)
- SNI = number of internal spars or longerons (one side, upper and lower)
- Q = quantity scaling factor
- 2 = operator for aerodynamic surfaces only (left and right)

Equation (4)

$$H_1 = 2\,(SPE+RP)\,(HT)\,(TJ4) \text{ (left and right)}$$

where

- H_1 = hours for panel fit and trim
- SPE = average spar perimeter in feet
- RP = average rib perimeter in feet
- HT = hours per lineal feet for fit and trim
- TJ4 = joint thickness ratio: 2 TS/0.04
- TS = average skin thickness

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
3		**Panel Fit and Trim - Fuselage**	Definition: The same task as for fuselage, however, the dimensional inputs, SPE and RP, are defined differently.
	(5)	$H_1 = (SPE+RP)\ (HT)\ (TJ4)$ where H_1 = hours for panel fit and trim SPE = average fuselage length RP = Average frame circumference HT = hours per lineal feet for fit and trim (differing from aero surfaces value)	
		Assembly Clamp And Layout - Aero Surfaces Or Fuselage	Definition: Clamping subassemblies into place in the assembly tool and layout of any nonlocated holes.
	(6)	$H_1 = 2\left[(RP)^R\ (RN)^Q + (SPE)^R\ (SNE+SNI)^Q\right]$ HL (left and right) where H_1 = hours for assembly clamp and layout R = size scaling exponent HL = assembly hours per unit length for clamp and layout Note: Definitional differences between aerodynamic surfaces and fuselage indicated above for the terms RN, SNI, SPE, and RP apply. For the fuselage, the computer program neglects the doubling of value indicated above.	
		Hole Drilling - Aero Surfaces or Fuselage	Definition: Hole drilling for mechanical fasteners.
	(7)	$H_1 = 2\left[(RP)^R\ (RN)^Q + (SPE)^R\ (SNE+SNI)^Q\right]$ (HD) (TJ4) (left and right) where H_1 = hours for hole drilling (not doubled for fuselage) HD = hours per foot for drilling	

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
3		**Finish Operations - Aero Surfaces or Fuselage**	Definition: Finish operations supporting installation of mechanical fasteners (reaming, countersinking, spot-facing, deburrring, cleaning of finish milling of rivet heads) or surface preparation for welding operations.
	(8)	$H_1 = 2\left[(RP)^R (RH)^Q + (SPE)^R (SNE+SNI)^Q\right] (HE)\ (TJ4)\ (FF1)$ (left and right)	
		where H_1 = hours for finishing operations (not doubled for fuselage) HE = hours per unit length for finishing FF1 = factor for fastener selection	
		Fastener Installation - Aero Surfaces or Fuselage	Definition: Installation of fasteners to complete the assembly.
	(9)	$H_1 = 2\left[(RP)^R (RN)^Q + (SPE)^R (SNE+SNI)^Q\right] (HFI)\ (TJ4)\ (FF2)$ (left and right)	
		where H_1 = hours for fastener installation (not doubled for fuselage) HFI = hours per foot for fastener installation FF2 = factor for fastener selection	
4		Secondary Structure Major Assembly Labor: **Aerodynamic Surfaces** **Assembly Task**	Definition: The assembly of secondary structure components to the structural box or basic structure. Excludes structure related to functional subsystems or items related to primary assembly.
	(12)	$H_1 = \left[(WRRP)\ (CSO) + 2(FSL) + 2(ERL) + 2(RSL)\right]^{WR} \times (TJ7)\ (FF3)\ (HEI)\ (CMB_1)$	
		where H_1 = component major assembly hours for aerodynamic surfaces WRRP = root rib length in feet CSO = center section operator: 1 without; 2 with FSL = front spar length in feet ERL = end rib length in feet RSL = rear spar length in feet WR = size scaling parameter	

FIG 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
4	(12) Contd	TJ7 = joint thickness ratio: 2TS7/0.04 TS7 = average skin thickness FF3 = factor for fastener selection HEI = cost per unit length for assembly CMB_i = complexity factor for assembly	
		Paint and Finish	
	(13)	$H_i = (AS2_i)(HS)(2)$ (upper and lower) where H_i = hours for paint and finish $AS2_i$ = surface area, ft^2 HS = hours per square foot for paint and finish	
		Fuselage - Nacelle - Landing Gear	
		Assembly Task	
	(14)	$H_i = CMB_i (RHP_i)(W_i)^{E_i}$ where H_i = component major assembly hours for fuselage, nacelle, landing gear CMB_i = a series of complexity factors related to the component estimated RHP_i = a series of reference hours per pound related to the component estimated W_i = total weight of the component estimated E_i = a series of weight scaling exponents	
		Paint and Finish (Excluding Landing Gear)	
		Same as Aerodynamic Surfaces except not multiplied by 2.	

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
5	(16)	Structural Material for Primary Structure: $$M_i = W_i^G (RMC_i)(SF_i) + W_i^G (RMC_i)(SF_i) + W_i^G (RMC_i)(SF_i)$$ where M_i = material cost for ribs, frames, spars, longerons and covers corresponding to inputs W_i = a series of weights for the components estimated: ribs, frames, spars, longerons, and covers. (Weight of finished structure) G = a series of weights scaling exponents RMC_i = a series of raw material costs per pound for each type of component estimated SF_i = a series of scrappage factors related to the material and component estimated	Definition: Production material used in the fabrication of primary structure components. Includes raw material, fasteners, clips and other standard hardware related to subassembly.
6	(17)	Structural Material for Secondary Structure: $$M_i = WD_i^G (RMC_i)(SF_i)$$ where M_i = material cost for secondary structure components WD_i = a series of weights for the secondary structure components being estimated G = a series of weight scaling exponents RMC_i = a series of raw material costs per pound for each type of component estimated SF_i = a series of scrappage factors related to the material and component estimated	Definition: Same as above except for secondary structure.

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
7	(18)	Basic Structure Assembly Material Cost: $$M_i = \left[\text{Primary Structure Assembly Labor}\right] \times (AMF1_i)(FM1_i)$$ where M_i = cost of material for primary structure assembly; $AMF1_i$ = a series of assembly material cost per labor hour factors related to the structural component being estimated; $FM1_i$ = a series of complexity factors related to fastener type used	Definition: Production material used in Primary Structure Major Assembly. Includes fasteners, clips and other standard hardware related to major assembly.
8	(19)	Component Assembly Material Cost: $$M_i = \left[\text{Component Assembly Labor}\right] \times (AMF2_i)(FM2_i)$$ where M_i = cost of material for component assembly; $AMF2_i$ = a series of assembly material cost per labor hour factors related to the structural component being estimated; $FM2_i$ = a series of complexity factors related to fastener type used.	Definition: Production material used in Component (Secondary Structure) Major Assembly. Similar to Basic Structure Assembly.
9	(15)	Rework: Rework Labor = Labor Subtotal × U where U = rework factor	Definition: Corrections and replacement of defective parts in the process of manufacture. Based on a percentage of original labor.

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
10		<u>Primary Assembly:</u>	Definition: This consists of the addition to the basic structure of elements related to the aircraft mechanical subsystems, such as hydraulic tubing, air conditioning ducting, engine inlet ducts, avionics, propulsion and armament provisions and other items that are integral to the structure but that are elements of functional subsystems. This task is dependent upon the design of the functional subsystems, and for trade study purposes is estimated on a percentage basis.
	(20)	Primary Assembly Hours = [Detailed Fabrication Hours + Subassembly Hours + Major Assembly Hours × % Factor]	
11		<u>Major Mate:</u>	This activity comprises the mating of the major structural subsystem into a complete airframe basic structure. It includes only the assembly related to basic structure. Examples are wing-fuselage mate and the mating of fuselage sections. The estimate is made by applying a percentage factor to the subtotal of manufacturing labor, excluding primary assembly.
	(21)	Major Mate Hours = [Detailed Fabrication Hours + Subassembly Hours + Major Assembly Hours × % Factor]	

RECURRING PRODUCTION COSTS

1		Recurring Production Cost by Structural Element	Definition: The costs, in three alternative quantities, including *RDT&E, obtained by learning curve projections* of detailed first unit cost.

(22)

$$\text{Cost estimated} = P1 \sum_{P2}^{P3} i^x$$

where

P1 = First unit cost

P2 = The beginning point of the projection

P3 = The ending point of the projection

i = The series of production units covered

$x = \dfrac{\ln P4}{\ln 2}$ where

P4 = The relevant learning curve factor expressed as a decimal fraction.

RECURRING PRODUCTION COSTS

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
2	--	Rework, Primary Assembly and Major Mate	**Definition: Previously used percentage factors applied to the totals obtained from the application of equation (22).**

NONRECURRING DESIGN AND DEVELOPMENT

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
1		Basic Structure Design Engineering Hours	**Definition: Basic structure design engineering comprises the detail design of the elements of basic structure plus such supporting activities as lines and lofting, checking, stress, weights, and value engineering as they relate to the element of basic structure.**
	(23)	$DEH_i = EH_i\,(WAMPR_i)^{EE}$	
		where	
		DEH_i = Design Engineering Hours	
		EH_i = Empirical estimating coefficient by structural component	
		$WAMPR_i$ = AMPR weight of the structural component being estimated	
		EE = Scaling exponent of engineering hours to weight	
2		Configuration Design Engineering Hours	**Definition: Configuration design engineering includes support engineering consisting of preliminary design, aerodynamics, dynamics, and thermodynamics activity relatable to structure.**
	(25)	CDEH = DEH × F1	
		where	
		CDEH = Configuration Design Engineering Hours	
		F1 = Factor for Configuration Design Engineering Hours	
3		Engineering Material	**Definition: Miscellaneous material and supplies, computer support, travel, per diem, and laboratory materials used in the design process.**
	(27)	EMD = CDED × F2	
		where	
		EMD = Engineering Material Dollar Cost	
		F2 = A Percentage Factor Applied to configuration design engineering dollar cost	

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
4	(28)	Basic Tool Manufacturing Hours $BTMH_i = TMF_i\ (WAMPR_i)^{ET}$ where $BTMH_i$ = Basic Tool manufacturing hours TMF_i = Empirical estimating coefficient by structural component ET = Scaling exponent, tool manufacturing hours to weight	Definition: Basic tool manufacturing hours are those required to produce a complete set of tools adequate to accomplish the manufacturing process. It is assumed that this set of tools will be capable of supporting a production rate of from one to three units per month.
5	(29)	Rate Tool Manufacturing Hours $RTMH = (\sum BTMH_i)\ (TAM^{ER} -1)$ where $\sum BTMH_i$ = (619, 7) SAV Matrix summation $RTMH$ = Rate tool manufacturing hours TAM = Monthly production rate ER = Exponent for scaling of rate tooling to production rate	Definition: Rate tooling is the tool provisioning required to increase production capability to a required rate.
6	(31)	Basic Tool Engineering Hours $BTEH = (\sum BTMH_i)\ F3$ where $BTEH$ = Basic tool engineering hours $F3$ = Decimal percentage: ratio of basic tool engineering to basic tool manufacturing hours.	Definition: The tool design and production engineering and planning required for the initial production set-up. This would typically be associated with flight test aircraft quantities.

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITIONS
7	(32)	**Rate Tool Engineering Hours** RTEH = (RTMH) F4 where RTEH = Rate tool engineering hours F4 = Decimal percentage: ratio of rate tool engineering hours to rate tool manufacturing hours.	Definition: Tool design and production engineering and planning required for increase to required production rate.
8	(34)	**Manufacturing Development and Plant Engineering Hours** MDPEH = TTMH × F5 where MDPEH = Manufacturing Development and Plant Engineering Hours F5 = Decimal percentage: ratio of MDPEH to total tool manufacturing hours.	Definition: Support to the manufacturing process by developing new techniques and processes and providing plant rearrangement.
9	(36)	**Tooling Material and Other Dollar Costs** TMOD = TTMH × F6 where TMOD = Tooling material and other dollar costs F6 = Per hour allowance for tooling material and other costs ($/hr)	Definition: Procurement of materials to support tool design and manufacture and the manufacturing support activities.
10	(37)	**Manufacturing Support Dollar Costs** MSD = CDED × F7 where MSD = Manufacturing support dollars F7 = Decimal percentage: ratio of MSD to configuration design engineering dollars	Definition: Vendor associated start-up costs and manufacturing activities in support of engineering design.

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITION
11		Quality Control Hours	Definition: Inspection and quality control activities during design and development to establish quality control procedures and inspection requirements.
	38	$QCH = (CDEH \times F8) + (TTMH \times F9)$	
		where	
		QCH = Quality Control hours	
		F8 = Decimal fraction: ratio of QCH to configuration design engineering	
		F9 = Decimal fraction: ratio of QCH to total tool manufacturing hours	
RECURRING AIRFRAME PRODUCTION COSTS (SUMMARY)			
1		Sustaining Engineering Hours	Definition: The engineering task concurrent with the production effort. An allowance for engineering support over and above a specific definition of tasks.
	(40)	$SEH = (DEH + CDEH)\ (PN2^{0.2} - 1)$	
		where	
		SEH = Sustaining engineering hours	
		DEH and CDEH: See Equations (23) and (25)	
		PN2 = RDT&E number of units	
2		Sustaining Tooling Hours	Definition: The task of maintaining tooling and production planning to support the production effort.
	(41)	$STH = (TTMH + TTEH + MDPEH)\ (PN2^{0.14} - 1)$	
		where	
		STH = Sustaining tooling hours	
		TTMH = Total tool manufacturing hours	
		TTEH = Total tool engineering hours	
		MDPEH = Mfg. development and plant engineering hours	

FIG. 21 REF.	EQ. NO. VOL. II	CER	DEFINITION
3		Manufacturing Summary: Detail Fabrication Labor Subassembly and Assembly Labor Material Costs	Definition: First unit costs for detail fabrication, subassembly and assembly combined, and production material costs summarized and projected over the quantity indicated using an aggregate learning curve value.
	(42)	$\text{Cost estimated} = P1 \sum_{i=1}^{P2} i^{x}$	
		where	
		$P1$ = First unit cost	
		$P2$ = The number of RDT&E units	
		$x = \frac{\ln P3}{\ln 2}$ where	
		$P3$ = The relevant learning curve factor expressed as a decimal fraction.	
4		Primary Assembly and Major Mate Hours	Definition: A summarization of primary assembly and major mate hours based on previously used percentage factor.
	(43)	$MML = [(632, 7) + (633, 7)]\ (MMPCTL)$	
		where	
		MMPCTL = Percentage factor	
5		Quality Control Hours	Definition: Previously used percentage factor applied to a summarization of detail fabrication, subassembly, assembly, primary assembly and major mate hours.
	(44)	$QCH = [(632, 7) + (633, 7) + MML]\ QCF$	
6		Primary Assembly and Major Mate Material	Definition: Production material used in primary assembly and major mate, estimated as a percentage of structural material.
	(45)	$MMM = (636, 8) \times MMF$	
		where	
		(636, 8) = Summation of material costs for structural elements	
		MMF = Major mate material percentage factor	

APPENDIX B

ORIGINAL AMVS PROGRAM SUMMARY

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224001
[redacted] WING CARRYTHRU STRUCTURE
AMAVS

JLM
/ /

PART NO.	NAME	MATERIAL	FACTORY	O. C.	TOOLS	TOTALS
4001	WCTS ASSEMBLY	$ 30,000	$ 165,670	$	$ 185,456	$ 381,126
3920	MLG SIDE BRACE	12,285	36,177		20,793	69,255
3930	XF 70 TRUNNION	9,058	15,494		12,743	37,295
3931	XF 95.5 TRUNNION	6,563	8,368		7,588	22,519
3941	MLG DRAG FTG.	9,572	18,334	13,623	17,729	56,358
3950	WING SWEEP FTG.	20,991	25,518		26,412	72,921
4006	PIVOT LUG RIB	1,403	1,650		1,432	4,485
4010	UPPER COVER	82,908	76,067		79,113	238,088
4030	OUTBD RIB	28,116	38,472		26,328	92,916
4060	BULKHEAD YF 992	63,138	69,451		75,478	208,067
4080	BULKHEAD YF 932	67,415	78,810		67,227	213,452
4110	CENTERLINE RIB	5501	14,585		19,159	39,245
4120	XF 39 RIB	11,639	25,451		14,683	51,773
4130	XF 84 RIB	4,901	9,130		16,737	30,768
4160	LOWER FAIRING	552	7,945		3,682	12,179
4170	LOWER PLATE	109,448	53,733		155,593	318,774
		$ 463,490	$ 644,855	$ 13,623	$ 727,153	$ 1,349,121

GENERAL DYNAMICS

APT PROGRAM

X7223920 - 1/2
MLG SIDE BRACE FITTING
AMAVS

J.L.M.
/ /

PART NO.	LH	RH	MC	EMC	MAT.	FAB.	O.C.	TOOLS
3920-1/2	1	1	TI	PMW	NA	11,759		10,883
3921-7/8	1	1	TI	PM	3,167	7,758		3,309
3922-7/8	1	1	TI	PM	866	1,997		597
3923-7/8	1	1	TI	PM	3,419	5,438		2,423
3924-7/8	1	1	TI	PM	4,833	9,225		3,581
TOTAL					12,285	36,177		20,793

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X 722 3930 - 7/8
[redacted] MLG TRUNNION FITTING - X_F 70

BY J.L.M.
PAGE 1 OF 1

PART NO	L.H.	R.H.	MC	FMC	MAT	FAB	Q.C.	TOOLS
3930-7/8	1	1	TI	PM	8,334	12,372		10,496
3932-7	2		TI	PM	724	3,122		2,247
					9,058	15,494		12,743

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7223931-7/8
[redacted] MLG TRUNNION FITTING - X_F 95.5
AMAVS

JLM
1 1

PART NO	LH	RH	MC	EMC	MAT	FAB	O.C.	TOOLS
3931-7/8	1	1	TI	PM	6,563	8,368		7,588

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X 7223941-1/2
[redacted] MLG DRAG FITTING ASSY
AMAVS

BY JLM
PAGE 1 OF 1

PART NO	LH	RH	MC	FMC	MAT	FAB	Q.C.	TOOLS
3941-1/2			TI	EBW	NA	3,049	13,623	8,002
3942-9/10			TI	PM	4,038	6,657		2,960
3943-9/10			TI	PM	3,333	5,270		2,738
3944-11/13			TI	PM	1,249	1,742		531
3945-9/10			TI	PM	952	1,616		498
					9572	18,334	13,623	14,729

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7223950-1/2
[redacted] WING SWEEP ACTUATOR FTG.
AMAVS

JLM
1 1

PART NO	LH	PH	MC	EMC	MAT	FAB	Q.C.	TOOLS
3950-1/2				INST	NA	NA		
3950-7/8	1	1		ASSY	NA	4,002		8,406
3901-9/10	2	2	TI	PM	18,954	20,470		17,687
3902-7	4		SS	BM	769	19		5
3902-9	4		SS	BM	1,153	19		5
3903-7	4		A2	PM	5	80		25
3903-9	2		A2	PM	29	428		133
3904-7/8	1	1	A5	PM	38	199		60
3904-9/10	1	1	A5	PM	38	235		71
3950-9-11-13	6		SH	S	5	66		20
					20,991	25,518		26,412

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

PART NO. X7224006 -71-8
[redacted] PIVOT LUG RIB
PRODUCT AMAVS

DATE
BY JLM
PAGE 1 OF 1

PART NO	LH	RH	MC	FMC	MAT	FAB	O. C.	TOOLS
4006-71/8	1	1	A5	PM	1,403	1,650		1,432

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X722 4010-1
[redacted] UPPER COVER ASSY – YF 932 TO YF 992
AMAYS

JLM
1 2

PART NO	LH	RH	MC	FMC	MAT	FAB	Q. C.	TOOLS
4010-1	1			ASSY	NA	NA		NA
4011-7/8	1	1	S1	PFM	61,004	28,087		48,442
4013-7/8	1	1	T1	PM	3,964	8,300		3,087
4013-9/10	1	1	T1	PM	4,052	7,624		2,799
4014-7	4		T1	PM	1,528	1,731		531
-9/10	2	2	T1	PM	903	1,154		348
4014-11/12	2	2	T1	PM	531	1,357		415
4015-7/8	1	1	T1	PM	465	1,077		332
4100-7	2		A5	PM	207	482		146
4103-7	4		A5	PM	25	175		53
4103-9	4		A5	PM	21	220		66
4150-1	1			ASSY	NA	936		284
4150-35	2		A4	SR	9	68		20
-37	2		A4	SR	1	15		5
4150-39	1			BOND	191	1,775		4,827
4150-7	1		A4	PM	310	476		144
-9	2		A4	PM	7	121		36
-11/12	1	1	A2	SF				
-13-15	2		A2	SF				

GENERAL DYNAMICS
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APT PROGRAM

X7224010-1
UPPER COVER ASSY - Y$_F$ 932 to Y$_F$ 992

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PART NO	LH	RH	MC	EMC	MAT	FAB	O.C.	TOOLS
4150-17	1		A2	SF	41	550		166
-27/28	2	2	A2	SF				
-29-31	4		A2	SF				
4150-19-33	4		C1	FAB	140	109		33
4151-1/2	1	1		BOND	264	2,047		8,696
4151-7/8	1	1	A4	PM	424	2,471		750
-9-11	4							
-13	2				22	652		199
-15 THRU-30	16	16	A2	EM				
-43 THRU-54	12	12	A2	EM	35	2,172		664
-31 THRU-36	3	3	C1	FAB	551	1,520		465
4151-111	2		A4	SR	37	877		265
4155-7/8	1	1	A5	PM	442	1,406		1,578
4156-7	2		A4	FR	21	412		124
-9/10	1	1	A5	PM	40	592		179
4157-7/8-9/10	2	2	T1	PM	6,913	8022		1,776
4159-7/8-9/10	2	2	A1	PM	760	1,639		2,683
					82,908	76,067		79,113

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224030-1/2
[redacted] OUTBOARD CLOSURE RIB ASSY
AMAVS

BY JLM
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PART NO	LH	RH	MC	FMC	MAT	FAB	Q. C.	TOOLS
4030-1/2	1	1		ASSY	NA	2,319		8,390
4031-7/8	1	1	TI	PM	4,889	3,726		3,153
4032-7/8	1	1	TI	PM	5,164	4,258		1,906
4032-9/10	1	1	TI	PM	4,810	5,215		2,304
4033-7/8-9/10	2	2	TI	PM	5,173	5,991		1,825
4034-7/8	1	1	TI	PM	2,874	5,639		2,368
-9/10	1	1	TI	PM	938	1,280		382
4034-11/12	1	1	TI	PM	1,079	1,909		581
4035-7/8	1	1	TI	PM	1,122	1,839		564
4035-9	2		TI	PM	415	723		216
4036-7-9	4		TI	PM	276	1,479		1,295
4036-11-13-15	12		AS	PM	962	2,505		2,512
4037-7/8	1	1	TI	PM	414	1,589		832
					28,116	38,472		26,328

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224060-1
BULKHEAD YF 992
AMAVS

JLM
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PART NO	LH	RH	MC	EMC	MATL	FAB	O. C.	TOOLS
4060-1	1			ASSY	NA	636		192
4061-1	1			BOND	528	2,989		7,149
4061-7	1		TI	PM	7,778	5731		8032
-9	2		TI	SR	442	52		17
-11	2		TI	SR	106	201		61
-13	2		TI	SR	137	37		10
-15	2		CI	FAB	46	17		5
-17	2		CI	FAB	110	85		27
-19	2		CI	FAB	60	84		25
-25 THRU 63	21	19	T	EM				
-63/70	2	2	T	EM	94	1,238		375
4061-71 -73	2	2	T	EM				
4062-1	2			BOND	47	928		2,483
4062-7	2		A4	SR	18	394		119
4062-9	2		A4	SR	3	177		53
-11	2		CI	FAB	55	84		25
-13 -15	4		A4	EM				
4062-23 -25	4		A4	EM	119	172		50
4063-7/8 -9/10	4	4	A4	SF	19	1,216		365

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224060 -1
BULKHEAD YF 992
AMAVS

JLM
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PART NO	LH	RH	MC	EMC	MAT	FAB	O. C.	TOOLS
4063-11/12	1	1	A4	SF	2	333		100
-13	6		A4	SF	3	140		41
-15	4		A4	SF	1	297		90
-17/18	3	3	A4	SF	3	442		133
-19/20	2	2	A4	SF	12	563		169
4063-21 THRU -24	2	2	A4	SF	1	312		95
4064-7/8	1	1	A4	SF	17	662		199
4065-7	2		A1	PM	2	297		90
-9	2		A1	PM	30	752		232
4065-11	2		A1	PM	22	446		133
4066-7	1		S1	PM	47	148		45
4066-9	1		A1	PM	2	159		48
4067-7/8	1	1	T1	PM	1,991	2,929		896
4068-7/8	1	1	T1	PM	1,798	1,719		514
4069-7/8	1	1	T4	SF	6	187		56
4070-7/8	1	1	S1	WELD	NA	11,557		31,645
4071-1/2	1	1	S1	WELD	NA	2,968		8,031
4071-7/8	1	1	S1	WELD	NA	4,460		1,360
4073-7/8	1	1	S1	PM	12,766	3,137		946

GENERAL DYNAMICS
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BULKHEAD YF 992
AMAVS

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PART NO	LH	RH	MC	EMC	MAT	FAB	Q. C.	TOOLS
4075-7/8	1	1	SI	PM	7,810	2,382		1,227
4071-9	2		SI	WELD	NA	3,033		4,838
4072-7	2		SI	PM	18,524	6,662		2,024
4074-7	2		SI	PM	6,117	4,084		1,244
4076-7	1		SI	PM	2,925	2,657		796
4078-7/8	1	1	TI	PM	729	2,043		614
4078-9/10	1	1	TI	PM	582	1,898		581
4104-7/8	1	1	AI	PM	48	642		141
4105-7	2		A5	PM	135	667		199
4109-9-21-23-41	8		P	SR	3	14		3
					63,138	69,451		75,479

[redacted]

X7224080-1
BULKHEAD YF 932
AMAVS

JLM
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PART No	LH	RH	MC	FMC	MAT.	FAB	Q. C.	TOOLS
4080-1				INST	NA	NA		NA
4082-1/2	1	1		BOND	430	3,757		5,098
4082-7/8	1	1	A1	PM	340	1,780		1,500
-9	2		A4	SR	20	193		58
-11/12	1	1	C1	FAB	187	235		71
-13	2		A5	PM	53	210		560
4082-15 THR-35	25	5	A4	EM	7	1,029		312
4083-1/2	1	1		BOND	494	2,713		7,862
4083-7/8	1	1	T1	PM	5,016	2,971		3,542
-9	2		T1	SR	373	41		13
-11	2		C1	FAB	219	55		17
4083-13 THR-36	17	11	TP	EM	256	622		189
4084-7	4		T1	PM	4,722	7,417		2,890
4085-7/8	1	1	S1	PM	1,361	1,704		514
4086-7/8,-9/10	2	2	T1	PM	↓	1,555		464
4086-11/12,-13/14	2	2	T1	PM	1,023	1,013		299
4087-7	4		S1	PM	1,342	1,092		332
4087-9	2		S1	PM	237	416		126
4088-7/8	1	1	T1	PM	1,612	2,119		647

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X 7224080-1
[redacted] BULKHEAD YF 932
AMAVS

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PART No	LH	RH	MC	FMC	MAT	FAB	Q. C.	TOOLS
4089-7	2		A5	PM	47	155		46
4089-9	2		A5	PM	43	296		90
4090-7/8	1	1	S1	WM	NA	14,335		19,338
4091-1/2	1	1	S1	WELD	NA	3,374		9,110
4091-7/8	1	1	S1	WELD	NA	2,628		796
4093-7/8	1	1	S1	PM	11,871	3,085		929
4095-7/8	1	1	S1	PM	7,671	2,200		1,268
4091-9	2		S1	WELD	NA	5,645		5,641
4092-7	2		S1	PM	15,575	7,525		2,289
4094-7	2		S1	PM	7,686	3432		1,045
4096-7	1		S1	PM	5,641	4,161		1,261
4098-7/8	1	1	T1	PM	658	1,120		332
4098-9/10	1	1	T1	PM	519	1,628		498
4066-7	2		A1	PM	1	151		45
4066-9	1		A1	PM	2	94		28
4109-49 THRU-71	14		P	SR	9	59		17
					67,415	78,810		67,227

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224110-1
CENTERLINE RIB
AMAVS

JLM
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PART No	LH	RH	MC	FMC	MAT	FAB	O. C.	TOOLS
4110-1	1			ASSY	NA	866		265
4109-7 THRU -47	9		P	SR	9	18		5
4111-1	1			BOND	337	1,554		7,099
4111-7/8	1	1	A4	SR	115	1,041		315
4111-9 THRU -23	5		P	FAB	183	348		106
4111 15,-17	2		A1	PM	4	143		43
4111-19,-25	2		A1	PM	24	141		43
4112-7, -9	2		A5	PM	1,130	1,521		465
4113-7/8	2		A5	PM	151	658		199
-9/10	1	1	A5	PM	153	1,481		448
4113-11/12	1	1	A5	PM	151	113		33
4114-7/8	1	1	A5	PM	1,104	2,006		2,766
4114-9	2		A5	PM	641	1,836		5,094
4118-7/8	1	1	A5	PM	1,083	1,880		1,983
4119-7	1		T1	PM	219	420		126
-9/10	1	1	T1	PM	197	560		169
					5501	14,585		19,159

GENERAL DYNAMICS
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APT PROGRAM

Part No. X7224120
Engrg. W.O. XF39 RIB INSTL
Project AMAYS ~ NBB

Cost Analysis

Date
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PART	NO	LH	RH	MC	EMC	MAT	FAB	O. C.	TOOL	T. FAB	T. TOOL	T. COST
4120					INST	NA	NA		NA			
4121	-1/2	1	1	A2	BOND	322	3,782		4,146			
4121	-7/8	1	1	A2	PM	510	1,473		1,988			
	-9	2		A2	SS	28	582		166			
	-11	4		A1	PM	117	220		66			
	-13	4		A1	PM	241	275		83			
	-17	2		A1	PM	443	756		1,408			
	-19	2		A2	SC							
	-21	2										
	-23	2										
	-25	2										
	-27/28	2	2			8	399		116			
	-29	2										
	-31	2										
	-33	2										
	-35	2										
	-37/38	2	2	A2	SC							
4121	-39/40	1	1	AC	S	263	63		17			

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224120
XF39 RIB INSTL
ANAVS ~ NBB

COST ANALYSIS

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PART NO	LH	RH	MC	FMC	MAT	FAB	O. C.	TOOL	T. FAB	T. TOOL	T. COST
4122-7/8	1	1	A1	PM	919	2,408		1,988			
4123-9/10	1	1	A1	PM	322	760		232			
4124-9/10	1	1	T1	PM	2,098	5,664		1,725			
4125-9/10	1	1	A1	PM	201	1,880		564			
4126-7/8	1	1	T1	PM	5,296	4,431		1,344			
4127-7	2		T1	PM	483	1,542		465			
4128-7	2		A2	PM	12	165		50			
-9	2		T1	PM	180	306		93			
-11	2		T1	PM	193	634		199			
4128-13	2		A1	PM	3	111		33			
					11,639	25,451		14,683			

GENERAL DYNAMICS
Fort Worth Division

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PART NO. X7224130-1/2
RIB X = 84
AMAVS

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PART NO	LH	RH	MC	FMC	MAT	FAB	O. C.	TOOLS
4130-1/2				INST	NA	NA		NA
4131-7/8	1	1	A5	PM	4,035	7,198		16,143
4132-7	2		A5	PM	243	464		141
4133-7/8	2	2	TI	PM	613	1,413		431
4109-59 -61	8		P	SR	2	4		5
4109-63 -65	4		P	SR	8	51		17
					4,901	9,130		16,737

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

PART NO. X722 4160-1/2
[redacted] LOWER FAIRING ASSY
AMAVS

JLM
1 2

PART NO	LH	RH	MC	FMC	MAT	FAB	Q. C.	TOOLS
4160-1/2	1	1		INST	NA	NA		NA
4129-7	2		A4	SR	1	28		8
-9	2		A4	SR	2	24		8
-11	2		A4	SR	3	39		12
-13	2		A4	SF	1	38		12
-15	2		A4	SR	1	199		60
-17	2		A4	SR	1	199		60
-19	2		A4	SR	2	233		70
4129-21/22	1	1	A4	SR	1	230		70
4162-11/12	1	1	TI	SF	118	477	-	144
-19	2		TI	SF	18	287		86
-25/26	1	1	TI	SF	12	212	-	65
-27	2		TI	SF	23	115		33
-29/30	1	1	TI	SF	84	650	•	199
-31	2		TI	SF	11	152		465
-33/34	1	1	TI	SF	56	351		106
4162-35/36	1	1	TI	SF	29	234		70
4164-7/8	1	1	A5	PM	132	868	x	1,120
4166-1/2	1	1		ASSY	NA	660	•	199

GENERAL DYNAMICS
Fort Worth Division

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X7224160 - 1/2
LOWER FAIRING ASSY
AMAVS

JLM
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PART NO	LH	RH	MC	FMC	MAT	FAB	O.C.	TOOLS
4166-7/8	1	1	A4	SF	18	215		66
4166-9-11-13-15	8		A4	SF	1	381		116
4167-7/8-9/10	2	2	A4	SF	33	760		232
4168-7-9-11-13	30		A4	SF	2	914		282
4169-7/8-9-15					↓	↓		↓
4169-11/12,13/14	7	3	A4	SF	3	680		199
					552	7,945		3,682

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

PART NO. X7224170
LOWER PLATE INSTL.
AMAYS ~ NBB

COST ANALYSIS

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PART	NO	LH	RH	MC	FMC	MAT	FAB	O.C.	TOOL	T. FAB	T. TOOL	T. COST
4170-1		1			ASSY	NA	(SEE 4001)		79,910			
4172-	1/2	1	1	TI	BOND	98	3,358		6,885			
4172	-7/8	1	1	TI	FM	5,711	3,215		3,969			
	-9	2		TO	SS	180	146		50			
	-11	2		TO	SS	168	77		23			
	-13	2		TO	SS	100	84		25			
	-15	2		TO	SS	45	197		60			
	-17/18	1	1	TO	SC							
	-19/20	1	1									
	-21/22	1	1									
	-23/24	1	1									
	-25/26	1	1									
	-27/28	1	1									
	-29/30	1	1									
	-31/32	1	1									
	-33/34	1	1									
	-35/36	1	1									
4172	-37/58	1	1	TO	SC	107	1,292		398			

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

PART NO. X7224170
ENGRG W.O. LOWER PLATE INSTL
PROJECT AMAVS ~ NEB

COST ANALYSIS

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PART	NO	LH	RH	MC	EMC	MAT	FAB	O. C.	TOOL	T. FAB	T. TOOL	T. COST
4172	-39/40	1	1	TO	SC							
	-41/42	1	1									
	-43/44	1	1									
	-45/46	1	1									
	-47/48	1	1									
	-49/50	1	1									
	-51/52	1	1									
	-65/66	1	1									
	-67/68	1	1									
	-69/70	1	1									
	-71/72	1	1									
	-73/74	1	1	TO	SC							
	-53, -55	2EA		AC	S	165	40		20			
4172	-57, -59	2EA		AC	S							
4173	-1	1		TI	B	368	2,511		6,402			
4173	-7	1		TI	PM	6,049	3,067		7,081			
	-9	1		TO	SS	1,071	229		50			
	-11, -13	2EA		AC	FAB	361	32		10			
4173	-15, -51	2EA		AC	FAB							

GENERAL DYNAMICS
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APT PROGRAM

PART NO. X224170
ENGRG W.O. LOWER PLATE INST'L
PROJECT AMHYS ~ NBB

COST ANALYSIS

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PART	NO.	LH	RH	MC	EMC	MAT	FAB	Q.C.	TOOL	T. FAB	T. TOOL	T. COST
4173	-17/18	1	1	TO	SC							
	-19/20	1	1									
	-21	2										
	-23/24	1	1									
	-25/26	2	2									
	-27/28	1	1									
	-29	1				101	1,024		315			
	-31	1										
	-33/34	1	1									
	-35/36	1	1									
	-37/38	1	1									
	-43	6										
	-45/46	2	2									
4173	-47	1		TO	SC							
4174	-7/8	1	1	A1	PM	675	1,738		7,867			
4175	-7	1		S1	PM	83,345	20,576		28,588			
4176	-7/8, -9/10	2	2	S1	PM (SEE 4175)		6,935		8,700			

GENERAL DYNAMICS
Fort Worth Division

APT PROGRAM

X7224170
LOWER PLATE INST.
A.MAKS

PAC - No	LH	RH	YC	FMC	MAT	FAB	O. C.	TOOLS
4050-7/8	1	1	A5	PM	313	1,859		1,198
4181-7/8	1	1	T1	PM	10,591	7,353		4,042
					109,448	53,733		155,593

APPENDIX C

AMAVS DETAIL PARTS - LISTING OF HOURS

Table C – Detail Parts, Listing of Hours.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4001	WCTS – Final Assy		11,438	524		3119.7	2447.	4691.6	$30,000.	5867
3920	FTG, MLG Side Brace		768.0	75.9		215	105.6	280.4	-	350.
3921	FTG, MLG SB Spt, Outbd		551.6	10.4		142		48.	3,167.	60.
3922	Web, MLG SB Spt.		138.8	5.5		36			866.	
3923	FTG, MLG SB Spt, Inbd		376.7	16.1		100		38.5	3,419.	48
3924	FTG, MLG SD Spt, Uppr		659.0	9.7		168		40	4,833.	50.
			2,493.6	117.6		661	105.6	406.9	12,285	508
3930	Trunnion – MLG – X_F 72.0		869.4	25.7		226.	N/CP: 326.8		8,334.	
3932	Cap, Trun. – MLG – X_F 72.0		212.0	13.0		57.		64.8	724.	97.
			1081.4	38.7		283	326.8	64.8	9,058.	97.
3931	Trunnion, MLG – X_F = 95.5		594.8	11.4		153	N/CP: 244.6		6,563.	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
3941-1/2	Drag FTG, MLG - Assy		191.3	26.6		305.	42.6	113		133.
3942-9/10	Drag FTG, MLG - Inbd. Beam		458.7	21.9		121.		48	4038	60
3943-9/10	Drag FTG, MLG - Outbd. Beam		369.2	11.9		96.		57.7	3333	72
3944-11/10	Drag FTG, MLG - Beam Ext.		111.8	13.0		32.			1249	
3945-9/10	Drag FTG, MLG - Splice		113.7	3.2		30.			952	
			1244.7	76.6		584.	42.6	218.7	9572	265
3950-7/8	Wing Sweep Actuator Su. Ass.		274.2	14.5		73	119.9	262.4		328.
3901	FTG, Wing Sweep Act. Spt.		1454.9	28.0		375	54.7	151.4	18,954	189.
3902-7	Bushing, Wing Sweep Actuator			1.2		.3	N/CP: 366		769	
3902-9	Bushing, Wing Sweep Actuator			1.2		.3			1,153	
3903-7	Splice, FTG, Supt., Wing Swp Act		3.9	1.7		1.5			5	
3903-9	Splice, FTG., Supt., Wing Swp Act		30.5	.5		8.0			29.	
3904-7/8	Flange, Wing, Swp. Act. Supt		12.1	2.1		3.6			38	
3904-9/10	Flange, Wing Swp. Act. Supt		14.6	2.2		4.3			38	
3950-9-10-11	Shims		3.9	.8		1.2			5.	
			1794.1	52.2		467.2	174.6 Total N/CP: 366	413.8	20,991	517.

Part No.	PART NAME	Wt.	Hours: Fabri-cation	Hours: Q.A.	Hours: Fabr. + Q.A.	Hours: Tool Planning	Hours: Tool Design	Hours: Tool Mfg.	Material: Fabri-cation	Material: Tooling
4006	Rib, Pivot Lug Y_F 944.15		106.9	11.4		30		47.1	1403.	59.
4010-1	Upper Cover Assy									
4011-7/8	Pivot Lug - Upper		1962.6	68.1		514	253.6	691.2 N/CP: 1095.4	61004	243
4013-7/8	Beam, Support - Upr. Cover		571.7	27.4		152		28.5	3964	36
4013-9/10	Beam, Support - Upr. Cover		541.2	11.0		140		24.0	4052	30
4014-7	Stiffener, Upper Cover		120.4	4.7		32			1528	
4014-9/10	Stiffener, Upper Cover		76.0	6.9		21			903	
4014-11/12	Stiffener, Upper Cover		91.4	6.3		25			531	
4015-7/8	Splice Strap, Upr. Cover Y_F 84; Y_F 932		74.6	3.2		20			465.	
4100-7	FTG, Fuel Hole Reinf.		32.5	2.2		8.8			207.	
4103-7	Clip, Attach-Skin Sup-Upr		11.7	.9		3.2			25.	
4103-0	Clip, Attach-Skin Sup-Upr		12.7	2.9		4.0			21.	
4150-1	Skin Panel - Upr - Center		40.8	24.0		17.1				
4150-35	Skin		4.8	.1		1.2			9.	
4150-37	Filler		1.1			3.			1.	
4150-39	Skin Assy - Panel		94.7	30.2		32.4	54.1	170.9	191.	214.

Part No.	PART NAME	Wt.	Hours						Material $	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4150-7	Skin		32.4	1.9		8.7			310.	
4150-9	Skin		8.7	.1		2.2			7.	
4150-11/12	Edge Members		30.9	8.0		10.			41.	
4150-19-33	Core		7.9			2.			140.	
4151-1/2	Skin Panel-U.S. X_F39-X_F84		100.	43.		37.5	50.0	365.1	264.	456
4151-7/8	Skin Panel-U.S. X_F39-X_F84 1st		110.5	7.5		30.			424.	
4151-7/8	Skin Panel-U.S. X_F39-X_F84 2nd		54.1	5.6		15.2				
4151-9, 11 13	Skin		45.3	1.8		12.			22.	
4151-15/16	Edge Member Panel		127.1	27.1		40.			35.	
4151-31/32	Core, Upr. Panel X_F39-X_F84		105.6	4.2		28			551.	
4151-111	Skin		63.7			16			37.	
			4322.4	287.1		1175.3	357.7	1279.7 N/CP: 109.54	74,914.	979
4155-7/8	FTG, Long Attach-Upper		84.	16.		1.8		78	442.	98.
4156-7	Splice Angle - Upr Skin		26.9	2.7		7.5			21.	
4156-9/10	Strap-Skin Upper X_F84		19.3	20.9		10.8			40.	
4157-7/8 & 9/10	Support - Fairing, Upper Cover		553.	26.1		15.6		76.4	6,913.	96.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4159-7/8 & 9/10	Beam, Skin - Upr Panel		107.4	10.4		30.		110.1	760.	138.
			5113.0	363.1		1241.0	357.7	1544.2 N/CP 109.54	82,908	1311
4030-1/2	Closure Rib Inst.		168.2	.2		42.	138.9	228.3 N/CP 51.8		285.
4031-7/8	Web		251.9	16.5		58	.3	105.9	4,889.	
4032-7/8	Support		293.4	14.0		78		30.8	5,164.	39.
4032-9/10	Support		365.7	11.5		95		37.7	4,810	47.
4033-7/8 - 9/10	Support		417.4	15.6		110.			5,173	
4034-7/8	Support		395.8	12.1		103.		33.2	2,874.	42.
4034-9/10	Support		83.1	8.7		23.			938.	
4034-11/12	Support		131.3	6.5		35.			1,079.	
4035-7/8	Support		127.3	5.5		34			1,122.	
4035-9	Support, Closure Rib		47.1	4.8		13			415.	
4036-7-9	Stiffener		105.8	1.4		27		42.7	276.	53.
4036-11-13-15	Stiffener, Closure Rib		173.2	7.7		46		88.2	962	110.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabrication	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabrication	Tooling
4037-1/2 (7/8)	FTG, Shear Link		107.7	6.8		29	8.	11.0	414	13.
			2667.9	111.3		693.	147.2	471.9 N/CP: 157.7	28,116	589.
4060-1	Bulkhead Y_F 992		46.2			11.6				
4061-1	Web, Assy		152.1	57.4		55.		314.5 N/CP: 304.7	528.	389.
4061-7	Skin		383.7	28.7		105.			7778.	
4061-9	Skin		2.9	.8		1.			442.	
4061-11	Skin		5.1	8.4		3.7			106.	
4061-13	Skin		1.9	.7		.6			137.	
4061-15	Core		1.2			.3			46.	
4061-17	Core		6.2			1.6			110.	
4061-19	Core		6.1			1.5			60.	
4061-25/ 26-63	Edge Member		76.2	12.1		22.6			94.	
4062-1	Cover, Assy		58.9	7.5		17.	29.	86.7	47.	108.
4062-7	Skin		26.7	1.7		7.2			18.	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4062-9	Skin		11.6	1.1		3.2			3.	
4062-11	Core		6.1			1.5			55.	
4062-13& 15, 23 & 25			12.5			3.			119.	
4063-7/8-9/10	Stiffener		82.9	4.8		22.			19.	
4063-11/12	Intercostal		21.9	2.		6.			2.	
4063-13	Intercostal		9.4	.7		2.5			3.	
4063-15	Intercostal		20.1	1.3		5.4			1.	
4063-17/18	Support		30.3	1.6		8			3.	
4063-19/20	Stiffener		39.4	1.3		10.2			12.	
4063-21-24	Support		18.6	3.6		5.7			1.	
4064-7/8	Stiffener		39.6	7.5		12.			17.	
4065-7	Splice		13.2	7.4		5.4			2.	
4065-9	Splice		52.9	1.5		14.			30.	
4065-11	Splice		29.7	2.4		8.			22.	
			1155.4	152.5		334.0	29.	401.2 N/CP: 304.7	9655.	497.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4066-7	Splice		7.7	2.7		2.7			47.	
4066-9	Splice		7.9	3.2		2.9			2.	
4067-7/8	Stiffener		207.4	4.7		54.			1991.	
4068-7/8	Flange		119.5	4.7		31.			1798.	
4069-7/8	Support		11.1	2.2		3.4			6.	
4070-7/8	Bulkhead Segment		770.6	60.7		212.	115.1	500.5 N/CP: 771.1		625.
4071-1/2	Bulkhead Segment		175.1	35.7		54.	65.7	304.6		381.
4071-7/8	Web Assy Weldment		247.5	67.5		82				
4073-7/8	Cap, Lower		216.4	10.1		57			12.766	
4075-7/8	Web, Bulkhead, Outbd.		164.6	7.4		44		25.1	7810	31.
4071-9	Bulkhd Segment		203.3	15.0		56	76.5	133.1		166.
4072-7	Cap, Upper		480.3	3.1		122			18524	
4074-7	Cap, Upper Outbd		266.8	26.3		75			6117.	
4076-7	Capt, Upper Center		176.4	14.6		48			2925.	
4078-7/8	Fitting		142.9	4.8		37			729.	
4078-9/10	Fitting		125.3	11.1		35			582.	
4104-7/8	Stiffener - 992 Blk		27.9	5.0		8.5			48	
4105-7	Beam, Spt. MLG Act. FTG		43.1	4.7		12.			135	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4109-9-2 23-41	Shim		1.			2.			3	
			4550.2	436.0		1272.5	286.3	1364.5 N/CP: 1075.8	63,138.	1700.
4088-1	Bulkhd - Y_F 932									
4082-1/2	Bulkhd Panel Assy		220.2	46.5		69.	41	164.9	430.	206.
4082-7/8	Skin		108.4	18.4		33		48.	240.	60
4082-9	Skin (inner)		14.0			3.5			20.	
4082-11/12	Core		17.1			4.3			187.	
4082-13	Edge Members		13.3	1.7		3.8		25.1	53.	31.
4082-15	Edge Members		38.5	32.		18.8			7	
4083-1/2	Bulkhd Panel Assy, Outb'd		154.6	37.5		50.	45.7	316.2 N/CP: 127.9	494	395.
4083-7/8	Skin		200.6	13.4		54	.3		5016.	
4083-9	Skin		2.2	.7		.8			373.	
4083-11	Core		4.			1.			219	
4083-13-36	Edge Member		41.	3.7		11.4			256.	
4084-7	Stiffener		512.5	23.1		136		32.	4722.	40.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4085-7/8	Gusset		98.5	22.3		31			1361	
4086-7/8 & 7/9	Gusset		93.6	17.1		28				
4086-11/12 & 13/14	Gusset		56.1	15.4		18			1023	
4087-7	Splice		61.9	15.4		20			1342	
4087-9	Splice		24.1	5.4		7.6			237.	
4088-7/8	Support		141.9	10.6		39.			1612.	
4089-7	Stiffener		10.1	1.		2.8			47.	
4089-9	Stiffener		18.9	2.3		5.4			43	
4090-7/8	Bulkhead Segment		1009.7	27.7		262.	1.	40. N/CP: 668.5		60.
4091-1/2	Bulkhead Segment (Pre Mach.)		207.8	32.9		62	65.7	352.3		441.
4091-7/8	Web Assy, Lower, Weldment		172.3	16.4		48				
4093-7/8	Cap, Lower		209.8	12.6		56			11871.	
4095-7/8	Web		155.1	4.1		40		30.5	7671.	38.
			3586.2	360.2		1005.4	153.7	1009.0 N/CP: 796.4	37,324.	1271.

Part No.	PART NAME	Wt.	Hours: Fabri-cation	Hours: Q.A.	Hours: Fabr. + Q.A.	Hours: Tool Planning	Hours: Tool Design	Hours: Tool Mfg.	Material: Fabri-cation	Material: Tooling
4091-9	Cap, Upper, Tee, Welded		398.3	10.3		103.	76.5	133.1		167
4092-7	Cap, Upper, Inbu		541.1	4.8		138.			15,575.	
4094-7	Cap, Upper, Outbd		247.3	1.7		63			7,686.	
4096-7	Cap, Upper, Splice		298.1	3.6		76			5,641.	
4098-7/8	Fitting		77.5	3.4		20			658.	
4098-9/10	Support		113.6	4.1		30			519.	
4066-7	Splice		8.1	2.5		2.7			1	
4066-9	Splice		5.	1.6		1.7			2.	
4109-49	Shim		4.3			1.3			9.	
			5279.5	392.2		1441.1	230.2	1142.1 N/CP: 796.4	67,415.	1438.
4110-1	Centerline Rib		35.7	24.		16.				
4109-11	Shim		1.3			.3			9.	
4111-1	Rib Assy		79.1	29.8		28.	58.8	285.6	337.	357.
4111-7/8	Skin		70.6	4.4		19.			115.	
4111-9-23	Core		25.3			6.4			183.	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabrication	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabrication	Tooling
4111-15-17	Insert		6.1	3.8		2.6			4.	
4111-19-25	Edge Member		8.0	2.0		2.6			24.	
4112-7, -9	Edge Member		105.8	4.1		28.			1130.	100
4113-7/8	Fdge Member		46.1	1.5		12			151	
4113-9/10	Edge Member		98.8	7.7		27			153	
4113-11/12	Edge Member		8.	.2		2.			151.	
4114-7/8	Beam		141.8	3.4		37.		*N/CP: 108.7	1104.	
4114-9	Beam		114.3	16.8		34	.2	*219.3	641.	
4118-7/8	Longeron		130.2	5.6		34		71.5	1083	89.
4119-7	Fitting		29.	1.3		7.6			219.	
4119-9/10	Clip		37.3	3.		10.2			197.	
			937.4	107.6		266.7	58.5	357.1 N/CP: 328	5501.	546.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabrication	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabrication	Tooling
4121-1/2	Panel; Rib - $X_F 39$		218.7	49.4		70.	59.	101.1	322.	126.
4121-7/8	Skin, Panel, Rib, $X_F 39$		96.8	9.		30.		75.1	510.	94
4121-9	Skin, Panel, Rib, $X_F 39$		42.3			10.			28.	
4121-11	Frame, Panel, Rib, $X_F 39$		16.			4.			117.	
4121-13	Frame, Panel, Rib, $X_F 39$		20.			5			241.	
4121-17	Frame, Panel, Rib, $X_F 39$		54.9			14			443	74.
4121-19 -38	Edge Member, Panel, Rib $X_F 39$		29.			7.			8.	
4121-39/ 40	Cure-Panel, Rib - $X_F 39$		4.6			1			263	
	Unnecessary Subtotal		482.3	58.4		141.	59.	176.2	1932	294.
4122-7/8	Beam, Lower-Rib, $X_F 39$		164.2	9.4		44.		63.4	919	79
4123-9/10	Flange, Rib-Upper, $X_F 39$		51.2	3.5		14			322	
4124-9/10	Flange, Rib-Fwd, $X_F 39$		402.6	7.7		104.			2097.	
4125-9/10	Flange, Rib-Aft, $X_F 39$		131.0	4.9		34			201.	
4126-7/8	Splice, Lower, $X_F 39$		309.2	11.1		81.			5296.	
4127-7	Plate, Splice, Y_F 947 Beam, $X_F 38.98$		104.5	6.6		28			483.	

Part No.	PART NAME	Wt.	Hours: Fabri-cation	Hours: Q.A.	Hours: Fabr. + Q.A.	Hours: Tool Planning	Hours: Tool Design	Hours: Tool Mfg.	Material: Fabri-cation	Material: Tooling
4128-7	Plate, Splice, X_F39		10.6	1.2		3			12.	
4128-9	Plate, Splice, X_F39		17.1	4.5		5.6			180.	
4128-11	Plate, Splice, X_F39		32.5	11.9		12.			193.	
4128-13	Plate, Splice, X_F39		6.9	1.0		2.			3.	
	Unnecessary Subtotal		1229.8	61.8		327.6		63.4	9706.	79.
	Total		1712.1	120.2		468.6	59.	239.6	11,638.	373.
4130-1/2	Rib, X_F84									
4131-7/8	Rib		500.3	19.8		131.	.2	*N/CP: 676.6	4035.	
4132-7	Flange		27.0	5.9		8.5			243.	
4133-7/8	Plate, Splice		94.7	7.		26.			613.	
4109-59 & 61	Shim		.3			.3			2.	
4109-63 & 65	Shim		3.7			1.			8.	
			626.0	32.7		166.8	.2	*676.6	4901.	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabri-cation	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabri-cation	Tooling
4160-1/2	Lower Fairing Assy									
4129-7	Doubler		1.8	.2		.5			1.	
4129-9	Doubler		.5	1.1		.5			2.	
4129-11	Doubler		2.4	.3		.7			3.	
4129-13	Doubler		2.4	.3					1.	
4129-15	Doubler		13.1	1.2		3.6			1.	
4129-17	Doubler		14.2	.2		3.6			1.	
4129-19	Doubler		7.5	8.3		4.2			2.	
4129-21/22	Doubler		15.8	.8		4.2			1.	
4162-11/12	Flange		33.1	2.		8.7			118.	
4162-19	Flange		18.6	2.		5.2			18.	
4162-25/26	Flange		13.1	2.		3.9			12.	
4162-27	Flange		7.2	1.		2.			23.	
4162-29/30	Flange		36.	9.9		12.			84.	
4162-31	Flange		10.6	.4		2.8			11.	
4162-33/34	Flange		23.9	1.4		6.4			56.	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabrication	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabrication	Tooling
4162-35/36	Flange		15.6	1.2		4.2			29.	
4164-7/8	Support		61.0	1.8		16.		42.9	132	56.
4166-1/2	Web, Lower Fairing, Assy		47.9			12.				
4166-7/8 9-11	Web		14.9	.6		4.			18.	
4166-13 15	Stiffener		25.4	2.		7.			1.	
4167-7/8 9/10	Support		50.3	4.3		14.			33.	
4168-7-9 -11-13	Stiffener		64.9	1.3		17			2.	
4169-7/8	Clip		36.1	11.7		12			3.	
			516.3	54.0		144.5		42.9	552.	56.
4170-1	Lower Plate & Lug Assy					585.	1039.6	2668.7		2669.
4172-1/2	Panel, Lower - X_F39 to X_F Assy		207.	32.6		61.	147.6	172.5	98.	216.
4172-7/8	Skin, Panel, Lower - X_F39 to X_F84		215.8	15.6		59.	4.	N/CP: 144.5	5711.	90.

Part No.	PART NAME	Wt.	Hours						Material	
			Fabrication	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabrication	Tooling
4172-9	Skin, Panel, Lower - X_F39 X_F84		10.4	.2		3.			180.	
4172-11	Skin, Panel, Lower - X_F39 X_F84		5.2	.3		1.4			168.	
4172-13	Skin, Panel, Lower - X_F39 X_F84		5.9	.2		1.5			100.	
4172-15	Skin, Panel, Lower - X_F39 X_F84		14.1	.2		3.6			45.	
4172-17/18	Edge Member-Pane, Lower X_F39 to X_F84		70.1	21.		24.			107.	
4172-53/55, 57/59	Core, Panel, Lower X_F39 to X_F84		2.9			1.2			165.	
4173-1	Panel-Web, Lower Plate-Center		145.	33.		50.	58.4	232	368.	290.
4173-7	Skin-Web, Lower Plate-Center		216.6	5.4		56.	1.3	N/CP: 296.9	6049.	
4173-9	Skin-Web, Lower Plate-Center		16.3	.3		3.			1071.	
4173-11-13-15-51	Core-Panel, Web, Lower, Plate-Cntr.		2.3			.6			361.	
4173-17/18 to 47	Edge Members-Panel-Web, Low Plt Cntr.		68.7	.5		19.			101.	

Part No.	PART NAME	Wt.	Hours						Material	
			Fabrication	Q.A.	Fabr. + Q.A.	Tool Planning	Tool Design	Tool Mfg.	Fabrication	Tooling
4174-7/8	Beam, Spt-Lower Plate, X_F98, 86		120.9	4.7		32.	.3	N/CP: 362.7	675.	
4175-7	Pivot Lug-Lower		1453.5	36.		377.	30.2	68.5 N/CP: 991.8	83,345.	86.
4176-7/8 9/10	Reinforcement-Pivot Lug, Lower		468.	31.5		127		N/CP: 319.4		
4050-7/8	Ftg, Lwr. Long, Attach		104.7	26.8		34		32.	313.	40
4181-7/8	Beam Y_F 947-MLG Brace		514.4	17.3		135		90.8	10,591	114.
			3641.8	230.1		1573.3	1281.4	3264.5 N/CP: 2115.3	109,448.	3505.

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